University of Alberta

Effects of Pre-Ozonation and Selected Advanced Water Treatment Processes on Mount Seymour Impoundment Water

by

Craig R. Bonneville ©

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Abstract

Three impoundments located in the Coast Mountains of British Columbia, Canada supply 1.7 million Greater Vancouver Region residents with drinking water. The Mount Seymour impoundment supplies 40 % of the water for Vancouver area residents. Low turbidity, organic matter content, alkalinity and hardness characterize its water. A dissolved air flotation/ozone/filtration pilot plant is located at the base of the dam. In May 1999 an 8-month pilot plant testing program was started to study the effects of pre-ozonation on the flocculation of particles and reduction of organic matter in an advanced treatment process. Results indicate that pre-ozonation slightly improves the flocculation of particles and their subsequent removal in the DAF unit. More significant is ozone's benefit for the reduction of UV-absorbing organic matter. The study also found that DAF is very effective at removing turbidity causing particles and colour from the water, thereby improving filter performance.

University of Alberta

Faculty of Graduate Studies and Research

The undersigned certify that they have read, and recommend to the Faculty of Graduate Studies and Research for acceptance, a thesis entitled *Effects of Pre-Ozonation and Selected Advanced Water Treatment Processes on Mount Seymour Impoundment Water* submitted by Craig R. Bonneville in partial fulfillment of the requirements for the degree of Master of Science in Environmental Engineering.

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1.0 Introduction

1.1 Project Background

Three impoundments located in the Coast Mountains of British Columbia supply approximately 1.7 million Greater Vancouver residents with drinking water. The Greater Vancouver Regional District (GVRD) operates the reservoirs, and delivers water to municipal districts which distributes drinking water. Capilano, Seymour and Coquitlam watersheds supply very high quality water, which is stored in three impoundments with a total surface area of 59,000 hectares. Each of the three watersheds receives heavy precipitation in the winter and is subject to rapid increases in turbidity due to elevated sediment transport and occasional mudslides at those times.

The Mount Seymour reservoir is located between the Capilano and Coquitlam watersheds and is sandwiched between Mount Fromme and Mount Seymour. A dissolved air floatation (DAF) / ozone / filtration pilot plant was built at the foot of the Seymour Dam to conduct research on these water treatment options with the goal of improving Vancouver's drinking water quality. Since the completion of the original studies for the GVRD (Reid Crowther, 1997), the pilot plant was made available by the GVRD for this study to investigate a variety of treatment options that may be applicable to other communities in British Columbia.

The last GVRD studies performed at the pilot plant were completed in February 1998. From that time to May 1999, the pilot plant was not used. With plans to perform structural work on the Seymour Dam, the pilot plant was scheduled to be disassembled and moved to a new location a safe distance away from the dam. In February 1999, a joint proposal with the University of Alberta (U of A) and the University of British Columbia (UBC) was submitted to a number of organizations active in this area of research. The proposed project involved two phases. The objectives for Phase I were primarily to study the effects of ozone on the flocculation of particles and the removal of organic matter in an advanced treatment facility (conventional treatment train with DAF instead of sedimentation). Phase II of the project focused on the effects of ultrafiltration membranes on treated water quality. Phase I of the Seymour Pilot Plant project was approved in April 1999 and commenced in May 1999. The purpose of this report is to discuss and evaluate the results of this study.

1.2 Previous Studies

Numerous studies have been performed at the Seymour Pilot Plant. The most recent study was the subject of the Seymour Filtration Plant Predesign Report, (Reid Crowther, 1997). The study was performed between April 1996 and March 1997 with the major objective of establishing design criteria for the future Seymour Water Filtration plant. That study was used as a reference for the current study so that unnecessary repetition was avoided and an efficient experimental method could be used.

1.3 Study Objectives

The primary objective of the pilot plant study was to obtain new information on the performance of various water treatment processes on Seymour Reservoir raw water. The study considered some seasonal water quality variations such as turbidity, particle counts, organic content and temperature. Specifically, the objectives of the study were to:

- evaluate the effects of different coagulants on the flocculation of turbidity causing particles;
- evaluate the effects of pre-ozonation on the flocculation of particles;
- evaluate the effects of ozone dose and coagulant type and dose on organic matter removal;
- evaluate the effects of flocculation conditions and DAF operating conditions on clarification performance; and

- study the effect of DAF on filter performance.

1.4 Water Quality Goals

Water quality goals for the duration of the pilot plant study are summarized below in Table 1.4.1. These values are for filtered water.

Table 1.4.1 Water Quality Goals

Parameter	Goal
Turbidity	< 0.1 NTU
Particle Removal	> 2.5 log for 3 to 5 μm
	> 2.5 for 5 to 15 μm
	> 2.5 for > 3 μm
Colour	< 5 TCU

Turbidity. Although turbidity does not pose a direct risk to public health in itself, it is considered to be aesthetically unappealing and may indicate the presence of microbial contamination. "The Guidelines for Canadian Drinking Water Quality", (Health Canada, 1996) list the maximum allowable concentration (MAC) for turbidity as 1.0 NTU. The aesthetic objective (AO) for turbidity is less than or equal to 5.0 NTU. The regulations established by the Environmental Protection Agency (EPA) in the United States are more stringent and may reflect future Canadian guidelines. Turbidity, while falling in the primary standard category, which means that the guideline is legally enforceable, is governed by the Interim Enhanced Surface Water Treatment Rule (IESWTR). The IESWTR took effect in February 1999 and applies to U.S. communities with over 10,000 persons. The primary purpose of the IESWTR is to control microbial pathogens such as *Cryptosporidium* spp and *Giardia lamblia* in drinking water. Water with high turbidity has a greater chance of microbial contamination, and therefore turbidity guidelines have been included. The turbidity guideline for filtered water effluent under this rule is less than or equal to 0.3 NTU in 95 percent of the measurements and may in no circumstances exceed 1.0 NTU. The goal of the American Water Works Association (AWWA) is to establish a guideline of

0.1 NTU in order to significantly decrease the risk of pathogenic contamination. Consistent with this guideline, a filtered water quality goal of 0.1 NTU was established for this project. Turbidity goals for individual unit processes were not established.

Particle Counts. Particle counts, if grouped into appropriate size ranges, can give a very good indication of potential contamination by organisms from 2 to 750 microns in size. This size range includes bacteria, algae, clays, silts, sands and cysts including *Giardia lamblia* (5 to 15 µm) and *Cryptosporidium* spp (3 to 5 µm). The "Guidelines for Canadian Drinking Water Quality" (Health Canada, 1996), list the maximum acceptable concentration (MAC) for coliforms as zero organisms per 100 mL. Since coliforms are only an indicator of pathogenic contamination, this guideline does not eliminate the chance of contamination by *Giardia lamblia* or *Cryptosporidium* spp. It appears that Health Canada is in the process of establishing guidelines for protozoa. Under the Surface Water Treatment Rule (SWTR) in the United States, municipalities that are required to use conventional filtration must achieve at least 2.5 log removal of *Giardia lamblia*. Municipalities that are required to use direct filtration are required to reduce *Giardia lamblia* by 2.0 log. Guidelines for *Cryptosporidium* spp are stll being established. Based on these guidelines, water quality goals for particle removal were greater than or equal to 2.5 log for the 3 to 5 µm (*Cryptosporidium* spp size range), 5 to 15 µm (*Giardia lamblia* size range) and >3 µm (floc particles) size ranges.

Colour. Colour is listed as an aesthetic objective (AO) with a value of less than or equal to 15 true color units (TCU) under "The Guidelines for Canadian Drinking Water Quality" (Health Canada, 1996). The USEPA classifies colour as a non-enforceable secondary guideline, also with a value of less than or equal to 15 TCU. The colour of water at these levels is detectable with an unaided human eye, and therefore a more stringent colour goal of less than 5 TCU was adopted for this study. Since only apparent colour samples were being analyzed for this study (i.e. turbidity interferences were not removed), samples with apparent colour less than 5 units would most certainly have a true colour of less than 5 units.

No other water quality goals were established for this study. Canadian and U.S. guidelines for pH are between 6.5 and 8.5 units to protect the distribution system and plumbing equipment from corrosion. Total organic carbon (TOC), dissolved organic carbon (DOC) and UV-absorbance do not have minimum requirements or guidelines listed under the EPA or Health Canada, however they are all commonly used as indicators of the organic content in water. Therefore, organic removal performance will be judged by a comparison to the Seymour Filtration Plant Predesign study and the current literature in this area. With any of the guidelines listed for turbidity, particle counts and colour, provinces and states have the option of adopting stricter guidelines, or instituting current guidelines as law.

2.0 Literature Review

2.1 Comparison of Conventional Treatment and DAF

Conventional water treatment plants use a multi-barrier philosophy for treating natural water for distribution to, and consumption by, the public. A multi-barrier approach uses numerous unit processes to treat natural water so that it is safe for human consumption. Specifically, conventional water treatment plants use the following treatment scheme:

(1) screening;
(2) coagulation/flocculation;
(3) sedimentation;
(4) filtration; and
(5) microorganism reduction (disinfection).

Sometimes the characteristics of the raw water or the objectives of the treatment process warrant the addition of a barrier or change in processes from the above treatment scheme. Dissolved air floatation (DAF) has been used as an alternative to sedimentation since the early 1900's to treat waters with low turbidity and low-density particles. For the purposes of this discussion, conventional treatment with DAF instead of sedimentation for clarification will be referred to as advanced treatment.

DAF is a clarification process where air that is saturated in water is released from a nozzle that is placed at the bottom of a clarifier (or flotation tank). When the air-water mixture is released into the water, the pressure drop from the saturator to the nozzle outlet causes the air to come out of solution and form small bubbles. These small bubbles then float to the water surface, attaching to floc particles along the way. The accumulated sludge at the top of the flotation cell is then mechanically skimmed from the water surface to a waste outlet. DAF is now emerging as a promising process for treating waters with low turbidity, low density particles, aquatic humic substances, natural color and/or algae, (Malley, *et al.,* 1991). The turbidity of water treated by DAF should not be greater than 100 NTU. In addition to the above advantages, there are indications that DAF is very good at preparing water for filtration.

The reason why a flotation process is more effective at removing low-density particles than sedimentation can be explained by Stoke's Law, which is applicable to discrete, spherical particles, Equation 2.1.1.

Equation 2.1.1 Stokes Law

$$V_s = \frac{g(\rho_s - \rho)d^2}{18\mu}$$

where, V_s is the settling velocity, m/s

g is the acceleration due to gravity, m/s^2

ρ_s is the density of the particle, kg/m^3

ρ is the density of water, kg/m^3

d is the particle diameter, m

μ is the dynamic viscosity of water, (N*s/m^2) x 10^{-3}

It can be seen that as the diameter of a particle decreases, the settling velocity of the particle will also decrease. In addition, as the water temperature decreases, the viscosity of the water increases, which will significantly decrease the settling velocity. The speed at which air bubbles rise will also be slowed, however, relative to how fast air bubbles rise when compared to the settling of particles, this effect is not as significant.

The high volume of bubbles created by the release of a saturated air-water mixture into the contact tank allows for a greater collision frequency in a DAF tank than in a gravity settling clarifier. Because of this, there will be more agglomeration of particles in the DAF tank, which will allow flocculation times to be shorter. Advantages of advanced treatment over conventional treatment for Seymour Reservoir water will be discussed in more detail in Section 2.4.

2.2 Coagulation and Flocculation Theory

Coagulation and flocculation is a process where a floc forming chemical, usually a metal salt, is added to a water or wastewater to promote particle destabilization or enmeshment of particles in a metal salt precipitate. The floc, large jelly-like particles that result from coagulation, is then removed by a clarification process such as sedimentation or flotation, depending on the size, density and concentration of the particles in the water. Coagulation is the addition of a coagulant to a rapid mix chamber for dispersion, and the subsequent destabilization of the fine, colloidal suspended solids, (Reynolds and Richards, 1996). Flocculation refers to the gentle stirring or agitation of the destabilized particles to promote particle collisions and the formation of a floc. Enhanced coagulation uses elevated coagulant doses and pH control to optimize floc formation, (Bell, *et al.,* 1996).

Coagulation focuses on the destabilization of colloidal particles that are too small to settle out in a sedimentation basin in a reasonable amount of time. A colloid is a suspended particle, organic or inorganic, smaller than 0.1 microns in diameter. Many microorganisms, such as bacteria, protozoa, humic and viruses, are small enough to act as colloids (1 to 10 μm). Most dissolved organic and inorganic materials found in natural water are hydrophilic, which means they have an affinity for water. These particles frequently have a negative charge on their surface. The role of the coagulant is to neutralize the charge on these particles so that they can adsorb onto one another to form a larger floc, or to form a precipitate that will trap smaller particles in its structure. The former is termed charge neutralization and the latter sweep flocculation.

Two interaction mechanisms account for the degree of attractiveness or repulsion of colloidal particles. Van der Waals forces are the universal attraction forces between atoms and molecules. They are a function of the distance between the particles and the size of the particles. The stability of particles, or degree of repulsion, is controlled by their electrical charge. These charges are caused by the ionization of hydroxyl and carboxyl functional groups at the particle's surface, imperfect crystal structures and the adsorption of ions from the water. A measure of the electrostatic potential at the particle's surface is called the zeta potential. The higher the zeta potential, the more stable a particle is in water. When counterions (usually positive ions) are introduced to the surrounding solution by the addition of a coagulant, they are attracted by the particle's electronegative charge. The positively charged ions come to rest in the diffuse layer of the colloid, that layer which surrounds the particle, or are attracted to the particles surface. Consequently, the overall charge of the particle is neutralized and therefore the zeta potential is reduced. Now that the influence of the electrical interactions between the particles is reduced, the van der Waals forces dominate, and the particles attract one another.

The chemistry of the sweep floc formation process is in very complex; however, simplified chemical relationships for alum in water are presented below to clarify the above discussion (Reynolds and Richards, 1996).

$$Al_2(SO_4)_3 \Rightarrow 2Al^{3+} + 3(SO_4{}^{2-}) \qquad [2.2.1]$$

$$Al^{3+} + H_2O \Leftrightarrow Al(OH)^{2+} + H^+ \qquad [2.2.2]$$

$$Al(OH)^{2+} + H_2O \Leftrightarrow Al(OH)_2^+ + H^+ \qquad [2.2.3]$$

$$Al(OH)_2^+ + H_2O \Leftrightarrow Al(OH)_3 \downarrow + H^+ \qquad [2.2.4]$$

$$Al(OH)_3 + H_2O \Leftrightarrow Al(OH)_4^- + H^+ \qquad [2.2.5]$$

Equation [2.2.1] shows alum ionizing in water to form a highly positively charged aluminum ion and a negatively charged sulfate ion. The sulfate ion is then associated with cations in the water. Equations [2.2.2] through [2.2.5] show the progression of the aluminum ion reacting with water to form hydrogen ions and aluminum hydroxide ions of different charges. The release of the hydrogen ions explains why the pH of the water decreases when alum is added. Equations [2.2.2] and [2.2.3] describe which reactions occur when charge neutralization is the desired removal mechanism. The aluminum and aluminum hydroxide ions that are formed will migrate to the electronegative particles and neutralized them. In equation [2.2.4], aluminum hydroxide solid is formed. It will then precipitate out and trap colloidal particles in its structure. This process is termed sweep flocculation. Which process occurs is dependent on the original amount of alum added, the time allowed for the reaction to occur and the amount of alkalinity that is present. A detailed discussion on the reaction kinetics can be found in Reynolds and Richards (1996). Figure 2.2.1 is a pc-pH diagram for aluminum hydroxide, (Reynolds and Richards, 1996). It shows that the minimum solubility of aluminum hydroxide occurs when the pH is between 5.5 and 7.5. Between these two pH's, aluminum hydroxide will be most easily formed.

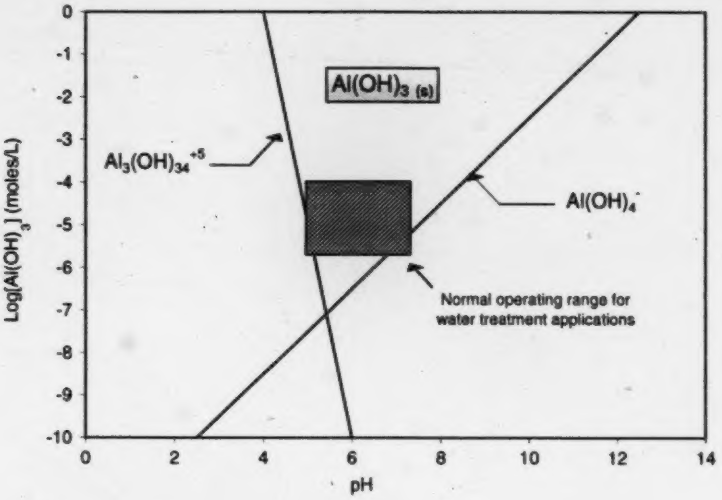

Figure 2.2.1 Solubility of aluminum hydroxide

The reactions for ferric chloride, another common coagulant, are similar to those for alum. Figure 2.2.2 shows the pc-pH diagram for ferric hydroxide, (Reynolds and Richards, 1996). The optimum pH range for sweep flocculation is between a pH of 5.5 and 7.5. If charge neutralization is desired, the goal would be to maximize the production of Fe^{3+} ions. Like alum, the addition of ferric chloride will decrease the pH, therefore, if it is too low, alkalinity may need to be added. The chemistry of polyaluminum chloride (PACl) is more complex than that of alum and ferric chloride, as it is not a pure substance, but a mix of many chemicals. However, optimum pH ranges are similar to those for alum and ferric chloride. Also, with PACl, very little alkalinity is required to keep the pH stable.

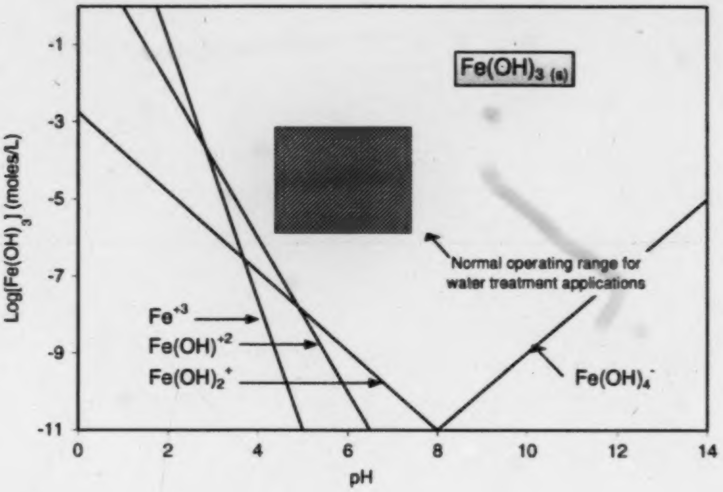

Figure 2.2.2 Solubility of ferric hydroxide

Equations [2.2.6], [2.2.7] and [2.2.8] below show why alum and ferric chloride require more alkalinity than PACl. For PACl, only one hydroxide ion is removed for every two aluminum ions whereas alum and ferric chloride use 3 hydroxide ions for each aluminum and iron ion consumed, respectively, (Schneider, *et al.*, 1991).

Alum: $$Al_2(SO_4)_3 \bullet 14H_2O + 6OH^- \Leftrightarrow 2Al(OH)_3 + 3SO_4^{2-} \quad [2.2.6]$$

$FeCl_3$: $$FeCl_3 + 3OH^- \Leftrightarrow Fe(OH)_3 + 3Cl^- \quad [2.2.7]$$

PACl: $$Al_2(OH)_5Cl + OH^- \Leftrightarrow Al_2(OH)_6 + Cl^- \quad [2.2.8]$$

There are a number of parameters other than coagulant dose and pH that influence the coagulation and flocculation process. The velocity gradient, G (s^{-1}), a measure of the intensity of the mixing environment, must be controlled in both the rapid mixing coagulation chamber, and the gentle mixing flocculation chamber. Rapid mixing must occur quickly and intensely so that all particles come in contact with the coagulant before precipitation can occur. The typical range of velocity gradients in rapid mix chambers is 700 to 1000 s^{-1} with detention times of 20 to 60 seconds, (Reynolds and

Richards, 1996). If static mixers are used, detentions times are much shorter (down to 1.0 s) and velocity gradients much higher (up to 2240 s^{-1}), (Valdade, *et al.*, 1996). To form a floc, gentle mixing is required in the flocculation chamber to induce contact between the destabilized particles, without ripping the floc apart. The typical range of velocity gradients for flocculation basins is 10 to 100 s^{-1} with detention times of up to 20 minutes. Detentions times when DAF is used as the clarification process can be as low as 5 minutes, (Valdade, *et al.*, 1996; Bunker, *et al.*, 1995). Polymers may be added at the same time as the coagulant to induce bridging to produce larger, although more fragile floc.

The number of particles in the influent water supply has a significant effect on the performance of the flocculation process. For flocculation to occur, destabilized particles must collide so that they can stick together and form larger particles. Water with low concentrations of suspended solids (turbidity) will have less of a chance for particle collisions to occur, and therefore poorer flocculation. Waste sludge is often seeded into low-turbidity water, before the coagulant is added, to increase the probability of contact between colloids. Two or three stage-tapered flocculation has been shown to produce a better floc, (Vrijenhoek, *et al.*, 1998). Tapered flocculation uses a series of flocculation tanks, each with a lower velocity gradient, to form large floc particles gently so that they are not broken apart. Floc size, floc density, water temperature and the characteristics of the influent water particles are important factors for determining clarifier detention times, (Vlaski, *et al.*, 1997). Sedimentation processes require dense floc particles with large diameters (>100 μm). For flotation to occur, particles less dense than water are required. Low velocity gradients and shorter detention times can form these types of particles. Shorter detention times will not allow the formation of large floc. Large floc particles are not required for flotation because the particles in the DAF process only need to attach to bubbles to float to the top of the tank. Section 2.4 will further describe this process.

2.3 Ozone as a Coagulant Aid

2.3.1 Theory

Ozone, although most commonly used as an alternative to chlorine for microbial reduction in drinking water treatment, has numerous other applications. Along with microorganism reduction, oxidation of inorganic pollutants, oxidation of organic micropollutants (taste and odour), and the oxidation of organic macropollutants, ozone when added to water, has a significant effect on particle behavior, (Reckhow, *et al.*, 1986; Singer, 1990). Although ozone is unable to act as a coagulant in the true sense of the word, it has been used extensively in Europe as an aid to coagulation, (Grasso, D., 1988). Some noted benefits of pre-ozonation or ozone-induced particle destabilization include decreased coagulant demand, increased filter run lengths, precipitation of natural organic matter (NOM), increased TOC / DOC removal and decreased sludge production, (Tobiason, *et al.*, 1990; Jekel, 1994). The emphasis of this discussion will focus on the secondary or coagulating effects of ozone rather than the primary or non-coagulating effects (microorganism reduction and oxidation).

Although the benefits of pre-ozonation are well documented and studied, the mechanisms by which these processes are carried out are poorly understood. This lack of understanding may be responsible for a number of inconsistencies in the reported results among some investigators. It appears that the mechanism, or combination of mechanisms, that occur in a given system is highly dependent on the amount and nature of NOM, and particularly DOC, in that system, (Jekel, 1994). Because more than one mechanism is thought to be occurring at one time in a system, it is difficult to relate the occurrence of a certain mechanism to a particular response in the system. In addition, it is not known whether one mechanism is dominant over the others. The situation is also complicated by the fact that the same mechanisms are not responsible for the removal of organic matter and the reduction of particles, (Jekel, 1994). However, it is apparent that what process occurs is dependent on the nature of the raw water being treated. The following is a list of six mechanisms, compiled by Reckhow, *et al.*, (1986), which appear to be responsible for the coagulating effects of ozone in natural waters.

1) The most commonly expressed mechanism that occurs in ozonated systems is the increased concentration of oxygenated functional groups. These groups, most notably the carboxylic acids, are theorized to form complexes with aluminum oxide surfaces, that will then bond to organic matter and precipitate out. The carboxyl acid group is a component of all organic acids and is most commonly expressed as '–COOH'. The properties of acids in relation to the formation of metal salts, is related to the number and arrangement of the carboxyl group, (Sawyer, C. N., 1994).
2) The increase in carboxylic acid groups may lead to an increase in calcium complexation and therefore the direct precipitation of organic matter. Complexation is when a metal ion associates with one or more molecules or ligands (Sawyer, *et al.*, 1994). Chandrakanth, *et al.*, (1998) showed that ozonation produced more ligand sites on NOM, leading to increased complexation with calcium and therefore the precipitation of organic matter with calcium carbonate, $CaCO_3$.
3) Ozone may affect the absorbency of organic matter by reducing the stabilizing effects of NOM on inorganic particles (Jekel, 1994). This will reduce the hydrophilicity of organic matter, and allow it to bond to air bubbles where flotation is the clarifying process being used.
4) The ozonation of NOM may lead to the formation of meta-stable organics that may undergo polymerization reactions. The polymers can act as flocculation aids by spontaneously precipitating, adsorbing to other surfaces, or bridging particles together.
5) Ozone oxidizes organo-metallic complexes and therefore releases metal ions such as Fe^{3+}, Fe^{2+} Mn^{4+}, and Al^{3+}. Once these ions are released into solution, metal coagulants may spontaneously form.
6) Ozone appears to have a strong affect on waters with higher concentrations of algae cells. Ozone can cause the lysis and destruction of algae cell walls,

thereby releasing various biopolymers, which will become more easily coagulatable, filterable or floatable.

This list is in no way an exhaustive one, and more mechanisms may occur when ozone is added to water. The major problem in this area of research is the limited knowledge of the chemical characteristics of DOC as fulvic and humic acids. It is clear that further investigation into ozone-NOM interactions is required.

2.3.2 Ozone-NOM interactions

One of the most desirable effects of ozone is improved TOC and DOC removal efficiencies as compared to direct filtration and conventional treatment approaches. When a coagulant (metal salt) is added to natural water, soluble NOM molecules are converted to insoluble NOM-coagulant complexes that are removed by direct precipitation or sorption of NOM onto precipitated coagulant products, (Edwards and Benjamin, 1992). When ozone is added to the system, the average molecular weight of NOM is decreased and the concentration of acidic functional groups increases, (Edwards, *et al.*, 1994), which affects the coagulant-NOM interactions, (Edwards and Benjamin, 1991). A decrease in the molecular weight of TOC will tend to decrease the tendency for organic matter to be removed by precipitation reactions with coagulants. An increase in the concentration of acid groups will tend to increase adsorption, but the decrease in the molecular weight of NOM will decrease adsorption. These conflicting mechanisms make the removal of NOM by sorption difficult to predict. Higher ozone doses will tend to favor a dominance of the adsorption process, whereas lower ozone doses favor the removal of NOM by precipitation, which is less efficient. Adsorption of NOM molecules, which are primarily anionic, onto floc surfaces will decrease the surface charge of the floc. This stabilizes them and makes them harder to remove, (Edwards, *et al.*, 1993). It is evident that there are two conflicting processes, therefore the goals of ozonation must be established to evaluate its benefits. If the goal is to reduce coagulant demand, then precipitation reactions must dominate. If the goal is to increase NOM removal, then sorption reactions will dominate, and the amount of coagulant needed will increase. Therefore, the combination of ozone dose and coagulant dose is very important for determining the removal of NOM from natural water. Removal of NOM may not be the only goal of ozonating water. Higher ozone doses, which would favor NOM removal, may decrease suspended particle removal (turbidity), decrease the rate of headloss buildup and decrease particle volume. These factors will be discussed further in the following section.

2.3.3 Benefits of Ozone as a Coagulant Aid

The coagulating effects of ozone were briefly discussed in Section 2.3.1. Although these general effects (better NOM removal, longer filter runs, reduced coagulant demand, improved particle removal, decreased sludge accumulation) are well documented, they are highly dependant on the nature of the water being treated. It is then difficult to formulate general conclusions without considering the characteristics of the raw water, and the treatment processes being employed following ozonation. In any case, pre-ozonation forms another component of a multi-barrier approach to water treatment, which is generally considered advantageous, (Gaubert, *et al.*, 1997).

From the discussion in Section 2.3.2, it is apparent that the quantity and type of NOM in the raw water has a large effect on whether pre-ozonation is beneficial for flocculation, (Chandrakanth, *et al.*, 1998). Depending on ozone and coagulant dose, TOC may be decreased without any reduction in DOC, or visa versa, (Edwards, *et al.*, 1992). Algae concentration seems to be important in determining ozone's benefits, but it is not crucial for it to be present to see benefits of pre-ozonation, (Reckhow, *et al.*, 1986). In general, it appears that the higher the ozone dose, the higher the removal efficiency of organic matter is, however, this is inversely proportional to particle and turbidity removal via precipitation with metal salts. Regardless, it is difficult to make firm conclusions on the effectiveness of ozone on the removal of DOC based on these scattered results.

Most investigators have found that ozone doses of 0.2 to 2.0 mg/L are most effective for a balance of optimum flocculation of particles and removal of organic material, (Reckhow, *et al.*, 1986; Ferguson, *et al.*, 1995; Jekel, 1994). The exact ozone dose required is water specific and must be determined in tests on that water. Low doses are used because it is not the goal of the pre-ozonation process to completely kill or remove the organic material in the water, but to alter its surface chemistry. Depending on the nature of the raw water and the ozone and coagulant doses applied, pre-ozonation can result in an anti-flocculating behavior, and an increase in the zeta potential of the particles being ozonated. The required ozone dose applied to a system has also been expressed as a concentration of ozone per unit of DOC. Typical values are 0.1 to 0.5 mg O_3 per mg of DOC, (Jekel, 1994). Typical DOC concentrations in Seymour impoundment are around 1.0 mg/L, which would make the optimum ozone dose based on this empirical relationship 0.1 to 0.5 mg/L. Section 5.0 will discuss experimental results and optimum ozone doses.

Ozone, by itself, is not a coagulant. It must be used in conjunction with another coagulant such as alum, ferric chloride or polyaluminum chloride to be effective. Again, which coagulant works best with ozone is dependent on the nature of the raw water. However, past studies have shown that alum with ozone works the best, although it is likely that alum has been used in more studies than any other coagulant, (Johnson, *et al.*, 1995). In most cases, ozonation does not improve particle reduction at the optimum coagulant dose, but facilitates particle reduction at a more economical coagulant dose, (Singer, 1990). Others have found that ozone had benefits as a coagulant aid, but not enough to justify its cost, (Schneider, *et al.*, 1991).

There is some disagreement as to whether ozone used as a coagulant aid results in better particle removal, or more importantly, results in a shift of the particle size distribution to larger diameters. These types of conclusions must be based on the nature of the raw water, and the treatment processes being used. In general, low ozone doses, usually less than 1.5 mg/L, helps to aggregate the particles so that they can be more easily removed by sedimentation or flotation, (Jekel, 1994; Gaubert, *et al.*, 1997; Ferguson, *et al.*, 1995; Johnson, *et al.*, 1995).

Perhaps the most significant effect of ozone on downstream treatment processes is the increased efficiency of the filters. This benefit is not particularly related to a better filter effluent, but to a decreased rate of filter headloss. In a study performed on Boston's low turbidity water, Johnson, *et al.*, (1995), found that unit filter run volumes (UFRV) were approximately twice the values that were achieved when ozone was not used as a coagulant aid. Other studies have yielded similar results, (Ferguson, *et al.*, 1995; Gaubert, *et al.*, 1997).

2.4 Dissolved Air Flotation

2.4.1 Theory of Operation

Dissolved Air Floatation (DAF) has been used as a solid-liquid separation process in water treatment for over 70 years, (Arnold, *et al.*, 1995). It is gaining popularity as a clarification process alternative to sedimentation for treating water with low-density particles. Although more commonly known as a separation process for wastewater and materials with lower specific gravity than water such as oils, fats and greases, its use for drinking water treatment is starting to gain popularity in North America. Though it is just an emerging technology in North America, it is widely accepted for potable water use in Scandinavia, the United Kingdom, South Africa, the Netherlands, Belgium and Australia, (Edzwald, 1995).

Because of the time required for settling out small, low-density particles with conventional clarification, particularly in cold water conditions, DAF can be a much more efficient process. Bacteria, algae, *Giardia lamblia* cysts and some precipitates produced from coagulation are particles that can have poor removals with conventional clarification, (Edzwald, *et al.*, 1992). Poor particle removal rates in the clarification stage will cause shorter filter runs because of the increased carryover of particles to the filters. Larger sedimentation basins, higher coagulant doses or greater flocculation times to produce larger floc would be required to overcome this problem.

Pretreatment processes prior to DAF are similar to those in conventional treatment plants. Rapid mixing with coagulant addition, followed by flocculation, is required to destabilize particles so that they may attach to air bubble surfaces effectively. Flocculation tanks are often considered to be the first stage of an integrated, two-stage DAF unit. The second unit is the flotation basin. Small air bubbles are released into the flotation tank, where they can attach to flocculated particles, and float to the surface where they are removed by mechanical skimmers. Air under pressures of approximately 480 kilopascals (kPa) is dissolved into recycled water in a unit called a saturator. The recycled water is most commonly clarified water from the DAF unit. Typically the saturator uses 6 to 10 percent of clarified water flow. The pressurized air-water solution is released into the flotation tank through a specially designed nozzle or needle valve. Because of the rapid drop in pressure from the saturator to the flotation tank (from 480 kPa to approximately atmospheric), small air bubbles form with diameters from 10 to 100 microns, typically 40 µm, (Zabel, 1984). Air bubble dispersion is controlled by a baffle that separates the reaction zone (where particle-bubble attachment occurs) and the separation zone (where particle-bubble conglomerates are already near the top of the clarifier), (MacPhee, *et al.*, 1996). The sludge that accumulates on the surface of the flotation tank in the separation zone normally has a dry solids density of 2 to 6 percent, depending on the raw water quality, coagulant dose and efficiency of the flotation process. The clarified water is collected at the bottom of the flotation tank by a series of perforated pipes.

Flotation tank design is similar to sedimentation tank design, except for their size. Flotation tanks can be much smaller than sedimentation basins because it takes much less time for bubbles to rise to the surface of a clarifier than for particles to settle to the bottom. Hydraulic loading rates in DAF clarifiers can be as high as 20 m/hr, as compared to approximately 1 m/hr for conventional clarifiers. Typical values for DAF design and operational parameters are located below in Table 2.4.1.

Table 2.4.1 Typical design and operation parameters for DAF

Parameter	Range	Typical
Saturation System		
Saturator Pressure (kPa)	350 to 620	480
Recycle Ratio (%)	6 to 30	6 to 12
Bubble Size (μm)	10 to 120	40 to 50
Clarifier Design		
Detention Time (min)	5 to 15	10
Depth (m)	1.0 to 3.2	2.4
Overflow Rate (m/hr)	5 to 15	8

The size, shape, volume and distribution of air bubbles are factors that affect the efficiency of particle removal, (Shawwa and Smith, 1998). Factors that control the characteristics of the air bubbles are the magnitude of the pressure change from the saturator to the flotation tank, the injection flow rate, the water temperature, the air temperature and the design of the injection nozzles. Smaller air bubbles are produced with higher pressure changes. In addition, higher saturator pressures create a larger volume of bubbles allowing for a greater chance of bubble-particle collisions, (Vlaski, *et al.*, 1997). The injection flow rate must be sufficient to prevent backflow to the saturator and bubble formation on the walls of the injection tube. The injection flow rate is determined by the recycle flow, and must therefore be designed carefully and efficiently so as not to waste too much clarified water. Because of the relationship between pressure and temperature, DAF operation may change with changing atmospheric conditions, (temperature, barometric pressure, and altitude). The size of the opening in the injection nozzle will affect the volume of bubbles released to the flotation tank. It will also affect the air-water mixture in the saturator by creating backpressure. The release of air from the nozzle must be accomplished with as little turbulence as possible so that floc particles are not broken apart.

Particles and bubbles interact in three possible ways, (Edzwald, 1995):

(1) entrapment of air bubbles in the floc structure;
(2) growth of bubbles in the floc structure; and
(3) particle-bubble collisions.

If the size of the floc particles is very large, mechanism (1) will predominate. Otherwise, mechanism (3) will be the dominant process. Collision frequencies are normally higher in DAF clarifiers than in sedimentation tanks, which allows flocculation times to be shorter. Mechanism (2) occurs to varying degrees under most conditions.

2.4.2 Pretreatment Effects

Coagulation and flocculation design is very important to ensure proper and efficient DAF performance. Table 2.4.2 shows coagulation and flocculation operating conditions when they precede dissolved air floatation (Edzwald, 1995). These results will be discussed in more detail in this section.

Table 2.4.2 Typical design and operating parameters for coagulation and flocculation

Parameter	Range	Typical
Coagulation		
Coagulant Type	Jar Test*	-
Coagulant Dose (mg/L)	Jar Test**	-
Ozone Dose (mg/L)	0.25 to 3.00	0.5 to 1.5
Flocculation		
Time (min)	5 to 30	20
Velocity Gradient (s^{-1})	10 to 150	70
Stages	1 to 3	2 to 3

* Alum, PACl etc.

** 4.0 to 30.0 mg/L depending on raw water characteristics

Flotation cannot occur without two necessary coagulation conditions, (Edzwald, 1995):

(1) charge neutralization; and
(2) production of hydrophobic particles.

Charge neutralization and production of hydrophobic particles prepare suspended matter for particle agglomeration and attachment to air bubbles, (Klute, *et al.*, 1995).

Charge neutralization or particle destabilization is accomplished by coagulation with a metal salt coagulant. The type of coagulant and its dose will determine how well a particle destabilizes (most often a reduction in its negative charge), although complete charge neutralization is not necessary. The choice of coagulant and its dose must be based on the characteristics of the raw water. Alum, ferric chloride and many polyaluminum chloride solutions have been used in DAF applications. However, similar to conventional treatment systems, alum is the most popular coagulant. Bunker, *et al.*, (1995) studied a number of coagulants on a number of different waters and found that all created favorable results when coagulant dose and pH were optimized. A stoichiometric relationship was developed to describe the amount of aluminum based coagulant required for every mg/L of DOC. This value was determined to be 1.0 mg of Al^{3+} for every mg of DOC at a pH of 7.0. However, it is important to note that this relationship was derived using water with NOM that may be different from water at Mount Seymour. Valdade, *et al.*, (1996), found no difference in DAF performance when alum or ferric sulfate were used. The authors noted that the process is very robust under a variety of coagulation and flocculation conditions. It is also generally accepted that PACls work better than alum in cold weather conditions, (MacPhee, *et al.*, 1996; Bunker, *et al.*, 1995). Polymers have been used in conjunction with coagulants for advanced treatment of drinking water, however, results are mixed (Vlaski, *et al.*, 1997). Bunker, *et al.*, (1995) found that an organic polymer benefited alum, but no PACl's when tested. Edzwald, (1995) noted that water with high concentrations of NOM have no need for the addition of an organic polymer to increase its hydrophobicity, and therefore enhance its ability to attach to air bubbles. Water with low concentrations of NOM needs the addition of high molecular weight anionic polymers after alum to increase particle hydrophobicity. In previous GVRD studies at the Seymour pilot plant, the addition of polymers did not improve particle removal in the DAF unit.

As noted in Section 2.2, ozone has a significant influence on the coagulation/flocculation process. Johnson, *et al.*, (1995), performed DAF pilot plant studies using different coagulants and pre-ozonation on water supplying Eastern Massachusetts. The water that supplies this region is similar to that which supplies the Greater Vancouver region in that it has generally high quality with low turbidity and low alkalinity. They found that ozone dramatically enhanced the removal of particles in the DAF unit. There was however no improvement in removal of assimiable organic carbon (AOC) in the DAF unit with ozone. It was also found that ozone worked best when used with alum.

The production of hydrophobic particles is the second criterion that must be fulfilled for proper flotation performance. Charge neutralization will partially decrease the hydrophilicity of some particles, but freshly formed precipitates such as aluminum hydroxide may still have water bonded to the surface even after charge neutralization. Performing runs at optimal pH and temperature minimizes this effect. Optimum coagulation pH can be determined from batch tests. Flotation seems to improve at higher temperatures (20°C). When the water is cold, the process of water thinning (water being displaced from the particle surface) is slowed, (Edzwald, 1995). Displacement of water from the surface of the particles is needed so that the particles can bond to air bubbles.

Proper flocculation conditions are necessary for good flotation performance. Although flocculation tank design for DAF is similar to those preceding conventional clarifiers, operating conditions are not the same. These operating conditions will be discussed in the following paragraphs. It should be also noted that sometimes flocculation tanks are integrated with the DAF clarifiers.

A reduction in the time needed for flocculation is perhaps the most significant difference between flocculator design for advanced and conventional treatment. Because there is a greater chance of bubble-particle collisions in DAF cells than particle collisions in sedimentation tanks, flocculation times can be reduced from 20 or 30 minutes to as little as 5 minutes (Johnson, *et al.*, 1995; Edzwald, 1995; Valade, *et al.*, 1996; Klute, *et al.*, 1995). Longer flocculation times create larger floc particles. However, it has been found that strong, pinpoint floc of less than 50 microns in diameter is desirable for good flotation performance, (Bunker, *et al.*, 1995). In fact, Valade, *et al.*, (1996) found that particles less than 10 microns are satisfactorily removed by floatation and large floc are therefore not needed. Decreased flocculation times will result in smaller flocculation tanks, saving space and money. Water production will increase because of shorter detention times, although other processes may limit production rate.

Flocculation mixing intensity is an important parameter as it is this slower mixing that allows particle collisions and subsequent agglomeration. A high intensity is required to disturb the water enough to increase collision frequency. However, too high a velocity gradient will create high shear forces that will rip-apart floc particles. In general, it appears that DAF turbidity and particle reduction percentages are best when mixing intensities are set at 70 to 100 s^{-1}, (Bunker, *et al.*, 1995; Valade, *et al.*, 1996; Klute, *et al.*, 1995). These higher mixing intensities produce a smaller, tougher pin sized floc desired for good flotation performance. The values for G are also higher than what are commonly used with sedimentation. However, Vlaski, *et al.* (1997), noted that better DAF performance occurred with mixing intensities as low as 10 s^{-1}. It appears that tapered flocculation, and 2-stage versus 3-stage flocculation has little effect on DAF performance, (Vlaski, *et al.*, 1997; Valade, *et al.*, 1996). It is clear that DAF performance with respect to flocculation design is very robust. Other flocculation design considerations are space, cost, ease of integration with other unit processes and power consumption.

2.4.3 Effects on Filter Performance

DAF has a significant advantage over sedimentation and direct filtration, particularly for treatment of waters with low-density particles. The increased removal efficiency of particles prior to filtration will allow longer filter runs (Edzwald, *et al.*, 1992; Ferguson, *et al.*, 1995; Edzwald, *et al.*, 1995). In addition, higher loading rates can be applied to the filters without any decrease in effluent quality. DAF also removes algae before it can plug the filters, which can significantly improve their performance (Johnson, *et al.*, 1995). Increasing filter loading rates and filter run lengths allows an increase in plant capacity resulting in considerable cost savings associated with filtration.

2.5 Surrogate Parameters for Organic Matter Determination

The organic carbon in natural water and wastewater is comprised of a number of different types of organic material in a number of different oxidation states. There exists no single parameter that accounts for all these different types of organic materials. Some carbon compounds can be oxidized by biological or chemical processes, which are represented by biochemical oxygen demand (BOD) and chemical oxygen demand (COD), respectively. Neither of these parameters is commonly used for evaluating natural waters because of the very small values they would produce. The total organic carbon content of natural water takes into account the BOD and COD fraction as well as the non-oxidizable organic material in the water. This means that it is independent of the oxidation state of the organic material. The TOC of water can be broken down into a number of fractions. These fractions are: inorganic carbon (CO_2, HCO_3^-, CO_3^{2-}), dissolved organic carbon (particles that pass through a 0.45 μm glass fiber filter), particulate organic carbon (particles retained on a 0.45 μm glass fiber filter), and volatile organic carbon, (Sawyer, *et al.*, 1994). TOC and DOC are the most commonly used parameters applicable to natural waters and drinking water treatment. UV-absorbance of water measures the absorbance of ultraviolet (UV) light by organic material. Some organic material, such as humic substances, tannin and lignin strongly absorb UV radiation. Each different type of organic material will most strongly absorb

UV light at a different wavelength, however, in the range of 240 to 270 nm, there is very little change in the absorptive capacities of natural waters, (Dobbs, *et al.*, 1972). A small plateau occurs at 253.7 nm, a therefore that value has been adopted as the standard (APHA, 1998).

Due to the cost of acquiring equipment for complicated analytical analysis of samples, and the time required to perform these tests, many surrogate parameters have been adopted for use in the measurement of water quality for water treatment. Turbidity is used as a surrogate parameter of suspended particulate matter. Colour is used as a surrogate measure of humic substances. The coliform group of bacteria is used as an indication of pathogenic microorganisms and UV-absorbance is now used as a surrogate measure of the total organic carbon content in wastewater and natural water, (Edzwald, *et al.*, 1985).

UV-absorbance is a good measure of naturally occurring organic matter such as humic substances as these types are abundant in natural water. Extreme pH differences may interfere with the absorbance of UV light, but this difference is minimal in the 6 to 8 pH range (Edzwald, *et al.*, 1985). Suspended particles (turbidity) may also absorb UV light, but they can be removed by filtration through a membrane with a 0.45 µm pore size.

A strong, linear correlation between UV absorbance at 254 nm and TOC has been found to exist for both raw water and treated water (Dobbs, *et al.*, 1972; Edzwald, *et al.*, 1985). In addition, this correlation has been shown to exist for water that has undergone a number of different treatment conditions, such as in a pilot plant study. Edzwald, *et al.*, (1985) noted in a pilot plant study that despite changing coagulants, flocculation conditions, process trains, filtration rates and pH's, that a good correlation existed between UV and TOC, even at different sampling points in the process. In fact, he found that almost the same surrogate parameter relationship existed for two different, although similar, water sources. Correlation coefficients between 0.85 and 0.87 were produced from two different studies, (Dobbs, *et al.*, 1972; Ezwald, *et al.*, 1985). These coefficients would be expected to improve, if pilot plant runs were performed under the same conditions.

An analysis was performed on Seymour impoundment water using UV and TOC data collected between 1997 and 1998 for the Seymour Filtration Plant Predesign Study, Appendix B. Figure 2.5.1 shows the linear relationship between TOC and UV for measurements taken from April 1996 through March 1998 on raw water samples collected at the Seymour pilot plant. The coefficient of determination for these data is 0.83, which is close to the values found in other studies. Correlation coefficients for data collected at other points in the treatment trains are not as good, which indicates that the treatment processes used in prior GVRD studies are only removing some of the organic constituents in the water.

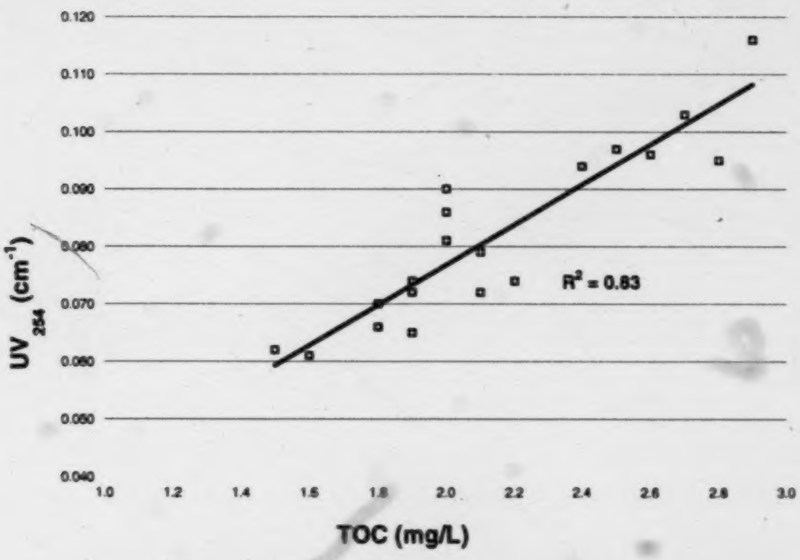

Figure 2.5.1 UV-absorbance and TOC correlation data for Seymour raw water

The addition of an oxidant such as chlorine or ozone may reduce the UV_{254} or color measurements, but may have little effect on the organic matter as measured as TOC. This is because oxidants do not cause the complete oxidation of organic matter to carbon dioxide. Instead, much of the organic matter is converted to organic byproducts (Edzwald, *et al.*, 1985).

3.0 Seymour Raw Water Quality

3.1 Historical Trends

Raw water quality data for the 7-year period from 1993 to 1999 were consolidated from GVRD's Laboratory Information Management System (LIMS). Monthly averages from that time period were calculated for July through December, coinciding with the pilot plant study period. The parameters chosen for this analysis were turbidity, temperature, pH, UV-absorbance at a wavelength of 254 nanometers (nm), colour, total organic carbon and dissolved organic carbon. Apparent colour and particle count data were not available from this information system.

Three watersheds supply water to Greater Vancouver's 1.7 million residents. The Mount Seymour watershed, located in the North Shore mountains of Vancouver, between Mount Fromme and Mount Seymour, supplies approximately 40 % of the water for the Greater Vancouver Region, despite being the smallest water supply reservoir. Capilano and Coquitlam are the other two watersheds on the North Shore. Table 3.1.1 summarizes the watershed characteristics.

Table 3.1.1 Watershed characteristics

	Seymour Watershed	Capilano Watershed	Coquitlam Watershed
Impoundment Size (ha)	262	312	1203
Watershed Size (ha)	18000	20000	21000
Impoundment Depth (m)	19	75	25
Impoundment Volume (X 10^9 L)	30	34	-
Population Supplied (%)	40	40	20

The water in the Seymour impoundment is normally of very high quality. All three watersheds are protected from human activities that may have adverse effects on their quality. This greatly restricts any development in the watershed. It also seriously limits public access. GVRD's lease of the watersheds from the Province of British Columbia requires the development of regular watershed management plans to address these issues.

The Seymour impoundment was created in 1924 by damming the Seymour River. In 1961, the dam was upgraded from a height of 6.7 meters to its current height of 30.0 meters. The Seymour watershed is mostly forested with coniferous trees native to the West Coast of British Columbia. This heavy forestation creates a natural filter that makes rainfall runoff very clear. However, some of the Seymour River floodplain is covered with easily erodable silts and sands that may make the reservoir water cloudy during periods of heavy rainfall. Unlike the clay deposits in the Capilano watershed, most of these silts and sands settle to the bottom of the reservoir before entering drinking water intake structures. This makes most turbidity events short.

The majority of the precipitation that occurs in Vancouver falls in the winter months. Average annual precipitation at the Seymour impoundment is approximately 3800 millimeters, while higher elevations average 5100 millimeters a year. Although the rainfall is necessary to replenish the reservoir that empties during the summer months, heavy rainfalls, particularly in the late fall and early winter, cause most of the turbidity problems and associated cloudiness in the drinking water.

The following paragraphs provide information on the yearly trends for the water quality parameters mentioned earlier in this section. Table 3.1.2 summarizes monthly averages from 1993 to 1999 for the selected parameters.

Table 3.1.2 Monthly Historical Means for Seymour Reservoir (1993 to 1999)

Parameter	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Turbidity (NTU)	0.93	0.64	0.92	0.53	0.35	0.36	0.39	0.48	0.57	0.71	1.82	1.88
Temperature (°C)	4.0	4.1	4.8	6.7	8.7	9.4	11.9	15.0	14.3	11.3	7.5	5.0
pH	6.3	6.3	6.2	6.3	6.3	6.3	6.3	6.3	6.3	6.3	6.3	6.3
UV_{254} (cm^{-1})	0.077	0.073	0.069	0.064	0.066	0.069	0.064	0.061	0.059	0.082	0.096	0.087
Colour (TCU)	13	13	12	11	11	12	12	12	12	14	16	15
DOC (mg/L)	1.9	1.8	1.7	1.6	1.5	1.7	1.6	1.5	1.3	1.9	2.3	2.2
TOC (mg/L)	1.9	1.9	1.8	1.8	1.7	1.8	1.7	1.7	1.6	2.0	2.5	2.3

Turbidity. Figure 3.1.1 presents the Seymour impoundment monthly, 7-year turbidity averages for January to December. The turbidity gradually rises from an average value of 0.39 NTU in July to an average value of 0.71 NTU in October. After this time the average turbidity rises steeply to a value of 1.82 for November. This steep increase corresponds with the start of the rainy season where most of the sediments deposited during the summer months are washed into the reservoir. Although the rains tend to continue through the winter, the turbidity does not continue to rise as steeply. This is because most of the sediments were washed away with the first few rainfalls of the season. In the time period between 1993 and 1999, the highest recorded turbidity value of 19.0 NTU occurred in November 1995. However, this type of event is quite rare. Ninety percent of the turbidity readings measured during this period were below 2.0 NTU.

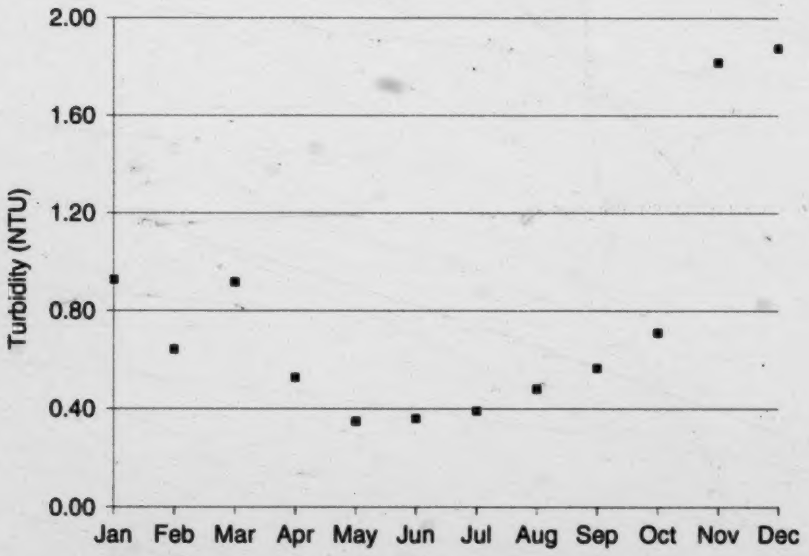

Figure 3.1.1 Historical raw water turbidity data (1993 to 1999)

Temperature. Maximum average monthly temperatures at the Seymour impoundment occur in August, while the lowest temperatures generally occur in January and February. Temperatures are fairly consistent from year to year and there are rarely any large fluctuations due to extreme warm or cold weather. Figure 3.1.2 shows monthly average temperature for January through December for the period between 1993 and 1999. Temperature changes from season to season may, however, be premature or delayed due to unseasonable weather.

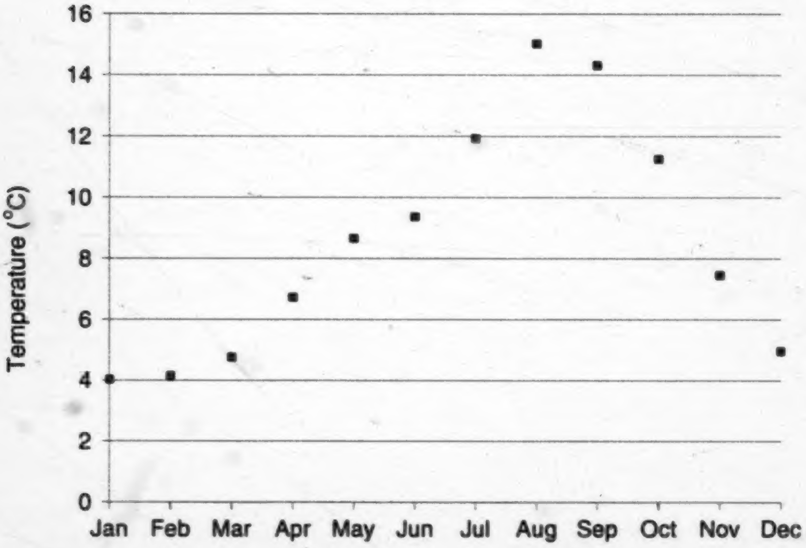

Figure 3.1.2 Historical raw water temperature data (1993 to 1999)

pH. The average monthly pH of the water in the Seymour impoundment for all months of the year is 6.3. Low pH causes corrosion problems in the distribution system. The "Guidelines for Canadian Drinking Water Quality" (Health Canada, 1996) lists an acceptable pH range as between 6.5 and 8.5. Because of this, GVRD has started adding soda ash to the water to bring it to acceptable levels.

UV_{254}. Absorbance at 254 nm is a measure of the amount of organic material in water and is often used as a surrogate measure of total organic carbon. Similar to seasonal trends seen for turbidity, Figure 3.1.3 shows the UV_{254} increasing from a value of approximately 0.060 cm^{-1} for July, August and September, to a maximum monthly average in November of 0.096 cm^{-1}. It is generally true that the UV_{254} for this water increases as the turbidity increases, however, as discussed in Section 2.5, this may not necessarily be true for all waters. The range of values for the time period between 1993 to 1999 was between 0.039 and 0.155, which indicates that UV_{254} measurements are less variable than turbidity measurements.

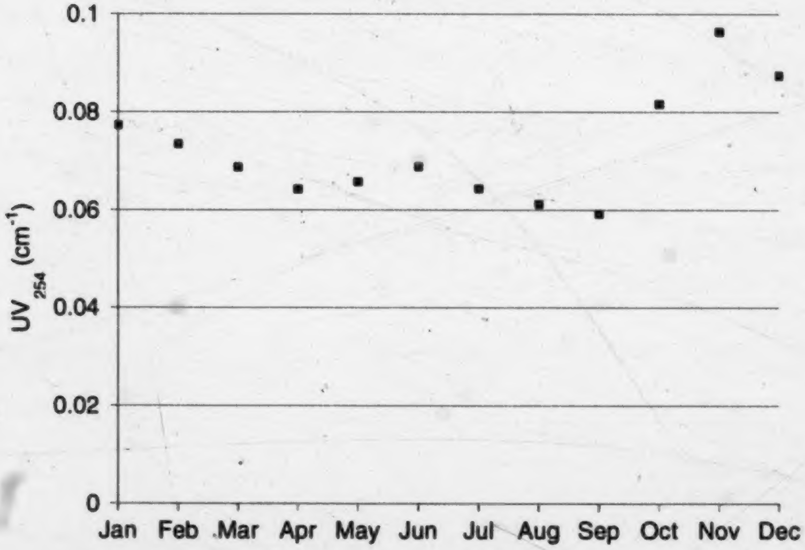

Figure 3.1.3 Historical raw water UV_{254} data (1993 to 1999)

Colour. Colour, like UV-absorbance, is an indication of the amount of organic matter in water. Reasons for its removal is more due to aesthetics, rather than health issues. As shown in Figure 3.1.4, colour follows the same monthly trend as UV_{254}. Average monthly highs and lows occur in November and July, with values of 16 and 12 TCU, respectively. The graph shows true colour, which means that turbidity interferences have been removed. Although it is apparent that historical monthly averages do not vary much, there have been isolated measurements of up to 29 TCU.

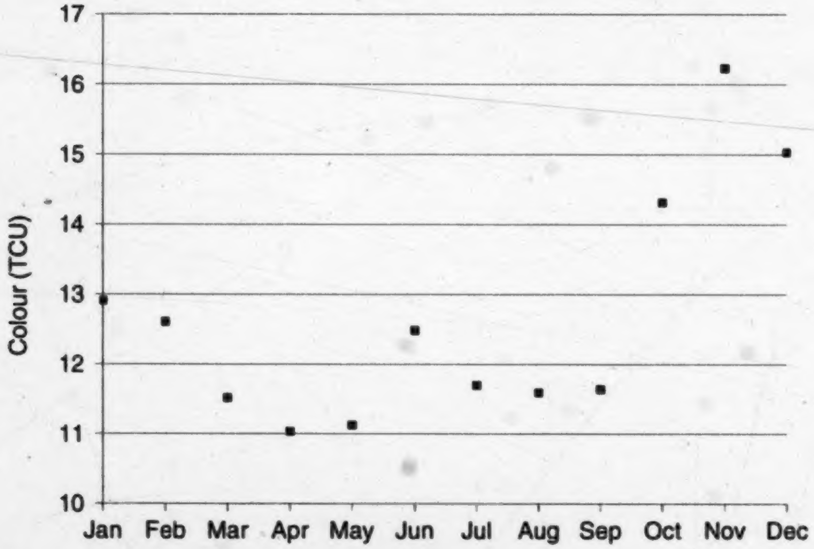

Figure 3.1.4 Historical raw water colour data (1993 to 1999)

TOC and DOC. Figure 3.1.5 shows monthly average TOC and DOC concentrations in the Seymour impoundment for the period between 1993 to 1999. Again, peak TOC and DOC concentrations occurred in November while the lowest values occur in the late summer. These values for TOC are 2.5 and 1.6 mg/L, respectively. DOC follows the same trend as TOC and has high and low values of 2.3 and 1.3 mg/L, respectively. These data indicate that the majority of the organic carbon in the water is in the dissolved form. Correlation data for TOC, DOC and UV_{254}, are located in Section 2.5.

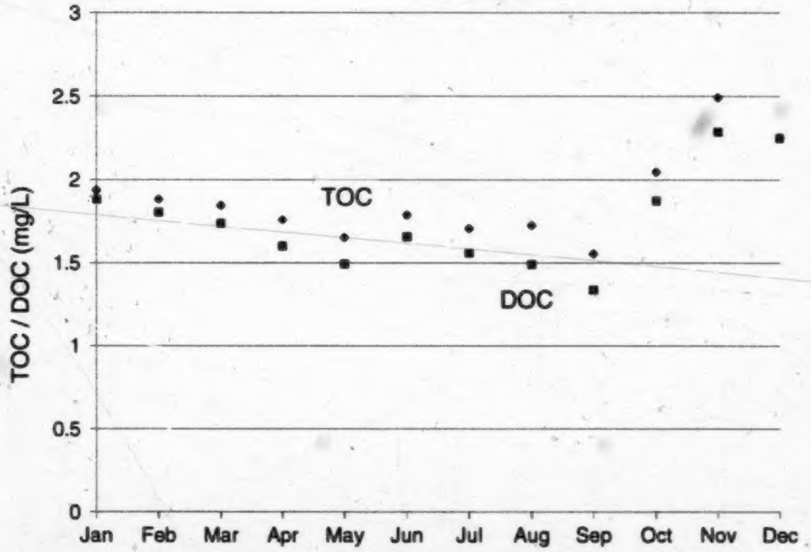

Figure 3.1.5 Historical raw water TOC and DOC data (1993 to 1999)

3.2 Pilot Study Period

Weather conditions during the pilot study period, between July and December of 1999, were quite different than normal conditions for that period. As a result, measured values for some water quality parameters were inconsistent with historical trends. The winter of 1998-99 saw some of the heaviest rain and snowfalls that have occurred this century on the West Coast. Subsequently, the North Shore Mountains had a very deep snowpack. In addition to this, a cool and wet spring delayed snowmelt and runoff by over a month. In fact, the snow never completely melted at higher elevation over the summer. The summer of 1999 was cool with less sunshine hours than normal, however, precipitation was not a lot above average. The months of September and October had greater than average sunshine hours and less precipitation than normal. As a result, the winter rains were delayed by a few weeks. This delayed the time that particles and organic matter increased in the reservoir by three to four weeks to the end of October, compared to the average.

Table 3.2.1 summarizes results of water quality measurements for the pilot plant study period. Shown are monthly means, means for the complete study period, the range of values for the complete study period and the number of samples measured and analyzed.

Table 3.2.1 Raw Water Summary Table for Pilot Plant Study

Parameter	Jul. 99	Aug. 99	Sep. 99	Oct. 99	Nov. 99	Dec. 99	Pilot Study Average	Pilot Study Range	Samples
Turbidity (NTU)	0.25	0.22	0.38	0.38	1.48	0.43	0.62	0.20 to 2.30	75
Temperature (°C)	9.4	10.3	12.8	8.9	6.7	5.6	9.3	4.4 to 13.8	71
pH	6.4	6.6	6.5	6.4	6.4	6.5	6.5	6.1 to 6.7	63
UV_{254} (cm^{-1})	-	-	0.062	0.068	0.106	0.080	0.082	0.039 to 0.127	53
Colour (ACU)	-	-	-	19	28	29	25	12 to 34	44
Particles (>2 µm) (#/mL)	482	389	613	692	3496	971	1351	346 to 5238	73
Particles (>4 µm) (#/mL)	232	191	280	351	1765	453	669	172 to 2902	73
Particles (>8 µm) (#/mL)	70	67	86	120	513	128	200	59 to 983	73
Particles (>16 µm) (#/mL)	0	1	1	2	3	1	2	0 to 10	73
Particles (>32 µm) (#/mL)	0	0	0	0	0	0	0	0	73
Particles (>50 µm) (#/mL)	0	0	0	0	0	0	0	0	73

Turbidity. Because of low runoff during the spring and summer and cool temperatures, the turbidity in the Seymour impoundment had lower than normal levels for most of the study period. Figure 3.2.1 shows daily turbidity data collected at the pilot plant during the study period. These data are compared to historical monthly averages calculated from 1993 to 1999. Monthly averages were below historical monthly means for each month in the study period. One significant turbidity event occurred between October 28 and November 16, where the turbidity rose to a maximum value of 2.30 NTU. This was due to the first major rainfall event of the winter season. However, the turbidity quickly returned to below historical averages. By November 26, the turbidity was below 1.0 NTU.

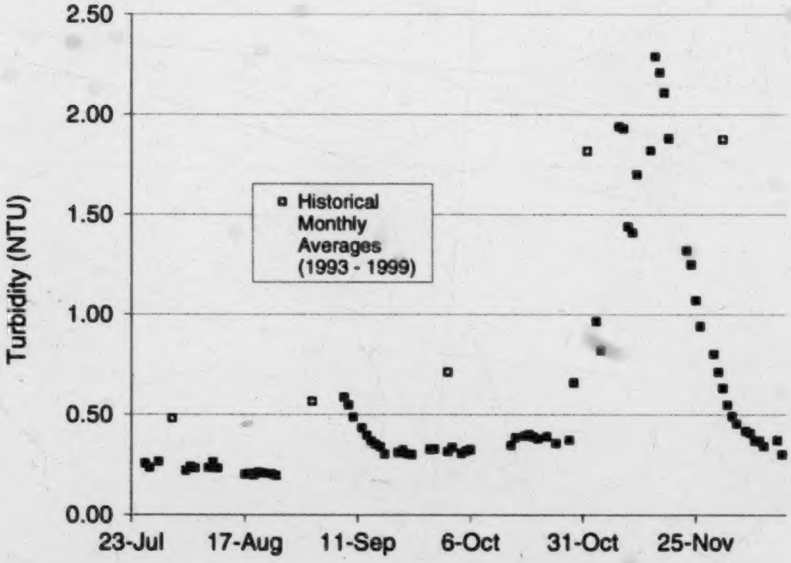

Figure 3.2.1 Seymour raw water turbidity data, 1999 (July 26 to December 14)

Temperature. The cool spring and summer, and late winter affected the temperature of the water in the reservoir. Average temperatures were well below normal for the months of July, August and September, but recovered to be at or slightly above historical averages for the rest of the study period. Figure 3.2.2 shows historical temperature data for the time period from 1993 to 1999 on the same chart with temperature measurements taken during the pilot study. A maximum reading of 13.8 °C occurred near the end of September, while the minimum value occurred on the last day of the study in the middle of December. This value of 4.4 °C was approximately 0.5 °C below normal for that time period.

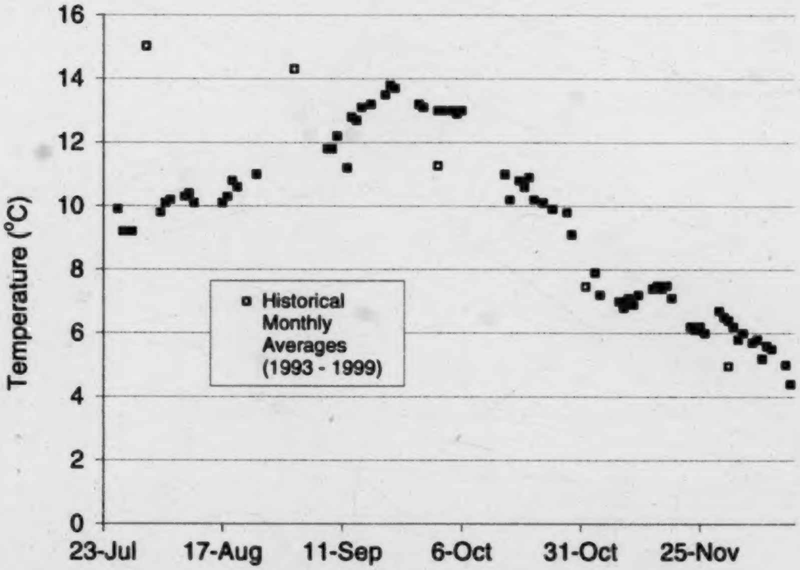

Figure 3.2.2 Seymour raw water temperature data, 1999 (July 26 to December 14)

pH. The historical mean pH of the water in the Seymour Reservoir for each month that the pilot study was carried out is 6.3. Figure 3.2.3 shows that samples collected during the study period ranged from 6.1 to 6.7 and had no discernable pattern. However, it is most likely that these variations were due to poor laboratory control and malfunctioning equipment, rather than actual variations in water quality. The average pH for the study period was 6.5.

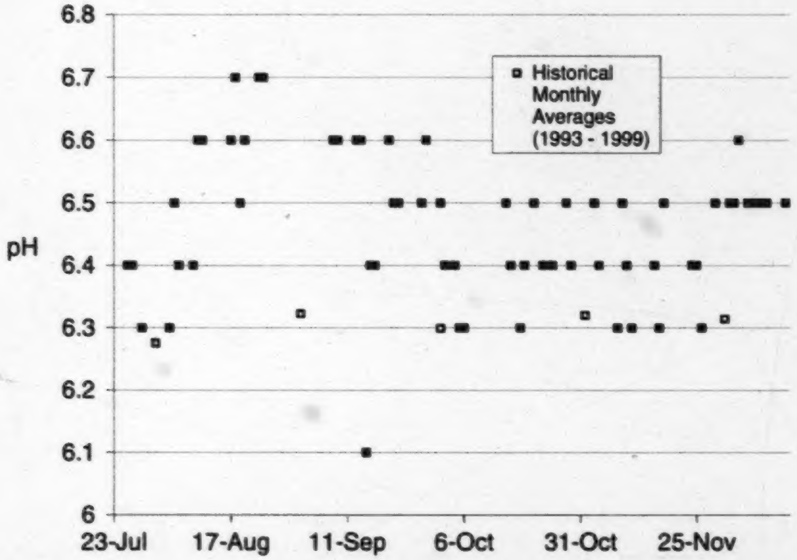

Figure 3.2.3 Seymour raw water pH data, 1999 (July 26 to December 14)

UV_{254}. Laboratory testing of the UV_{254} of the water did not start until the middle of September due to problems acquiring a suitable spectrophotometer. Figure 3.2.4 shows that measured values agree quite well with historical trends. It also appears that the turbidity event that occurred for the first two weeks in November was accompanied by a proportional increase in the amount of organic matter in the water. The maximum UV-absorbance reading occurred during this event. The maximum recorded value on November 16 was 0.127 cm^{-1}. Since no TOC or DOC measurements were taken, UV_{254} was used as a surrogate parameter for these two parameters.

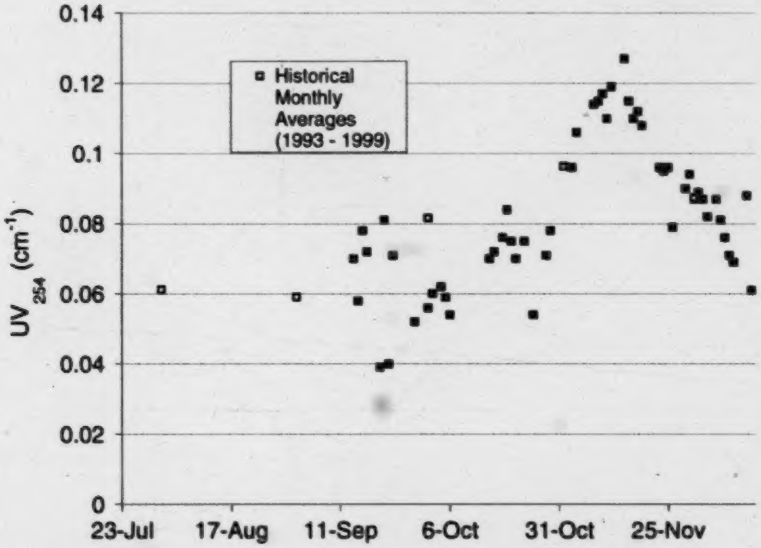

Figure 3.2.4 Seymour raw water UV_{254} data, 1999 (July 26 to December 14)

Colour. Only apparent colour readings were taken during the pilot study, therefore comparison to historical true colour readings is difficult. Table 3.2.2 shows that the highest colour reading occurred after the winter rains started in November. Average values ranged from 19 ACU in October to 28 ACU and 29 ACU in November and December, respectively. Colour readings were relatively consistent throughout the study period. Figure 3.2.5 shows apparent colour values for the study period.

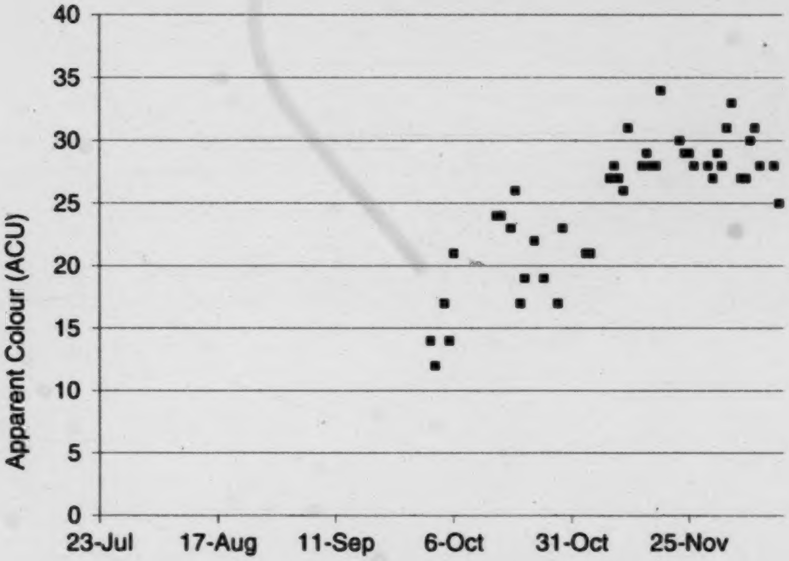

Figure 3.2.5 Seymour raw water apparent colour data, 1999 (July 26 to December 14)

Particles. Figure 3.2.6 shows particle counts per milliliter in the size ranges of >2, >4, >8, >16, >32 and >50 microns. These size ranges include the sizes of typical bacteria, clays and silts, as well as *Giardia lamblia* and *Cryptosporidium* spp. Particle counts for the study period were consistently low until the high turbidity event that occurred at the beginning of November. During this time, particle counts in the 2 to 4 micron range increased by nearly 1000%, (x 10). Similar to the trend for turbidity, the particles dropped rapidly to levels comparable to summertime values by the end of the study period. Larger particle size ranges followed the same trends as the smaller particle ranges.

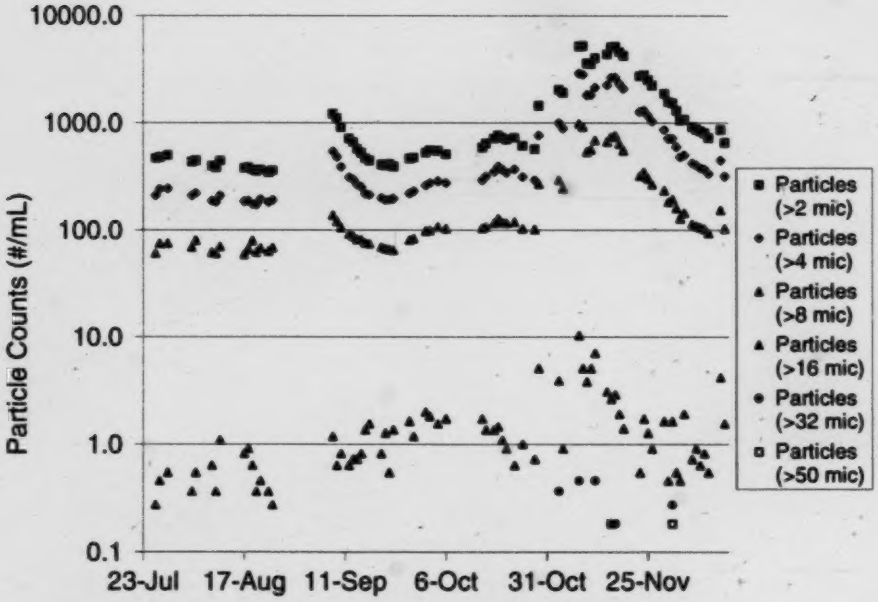

Figure 3.2.6 Seymour raw water particle data, 1999 (July 26 to December 14)

4.0 Experimental Design and Methods

4.1 Pilot Plant Description

A detailed pilot plant description and operation manual is located in Appendix A. The GVRD Seymour Pilot Plant is located at the base of the Seymour Falls Dam, to the southwest of the chlorine building, and has a footprint of 107 m^2 (Figure 4.1.1). The sludge handling tanks, coagulation tanks, ozone generation equipment and columns, filter columns and laboratory are located on the main level. The DAF unit, static mixers, flocculators and access to the tops of the filter columns are located on the mezzanine level above the lab. Unit processes used for the pilot study are as follows:

- pre-ozonation;
- coagulation (rapid mixing in static mixers);
- flocculation;
- dissolved air floatation; and
- filtration.

Figure 4.1.1 Seymour pilot plant

4.2 Plant modifications

None of the previous pilot plant studies performed at the Seymour Pilot Plant considered ozonation of water before the addition of coagulants and clarification in the DAF unit. As a result, there was no existing piping system that allowed ozonated water to go directly to the DAF unit. In addition, the three sets of ozone columns (labeled A, B, and C), each with two contactors (labeled 1 and 2) were designed to handle flows too small to attain reasonable DAF loading rates. Each set of ozone columns was equipped with a rotameter capable of handling flows from 0 LPM to approximately 40 LPM for a total ozone flow in all three sets of columns of approximately 120 LPM running at maximum capacity. However in practice, under the existing set-up, only about 80 to 100 LPM could be pushed through the three sets of columns. The surface area of the DAF flotation cell is 0.7 m^2, therefore a 100 LPM flow into the unit gives a loading rate of 8.6 m/hr. Each set of ozone columns leads to a separate ozonated water storage tank. Each of the tanks feeds water along a different process train. A pump is attached to each of the discharge lines from the tanks and moves water to a second floor unit process. Only pump 2 leads to the DAF unit. In order to attain a high enough pumping capacity to lift over 100 LPM of water to the DAF unit, the pumps were placed in a modified parallel position (Figure 4.2.1). Each pump is still paired with its own storage tank, but the outlets join into one 50 mm line that leads to the static mixers and DAF unit on the mezzanine level. This configuration should allow a theoretical total capacity of 150 LPM, assuming the level in each storage tank is the same and the distance from the water level to the mezzanine level is 3.0 m. However, in practice, the capacity was much lower. As it turned out, the pumps, rather than the capacity of the ozone columns, was the limiting factor for water transport to the DAF unit.

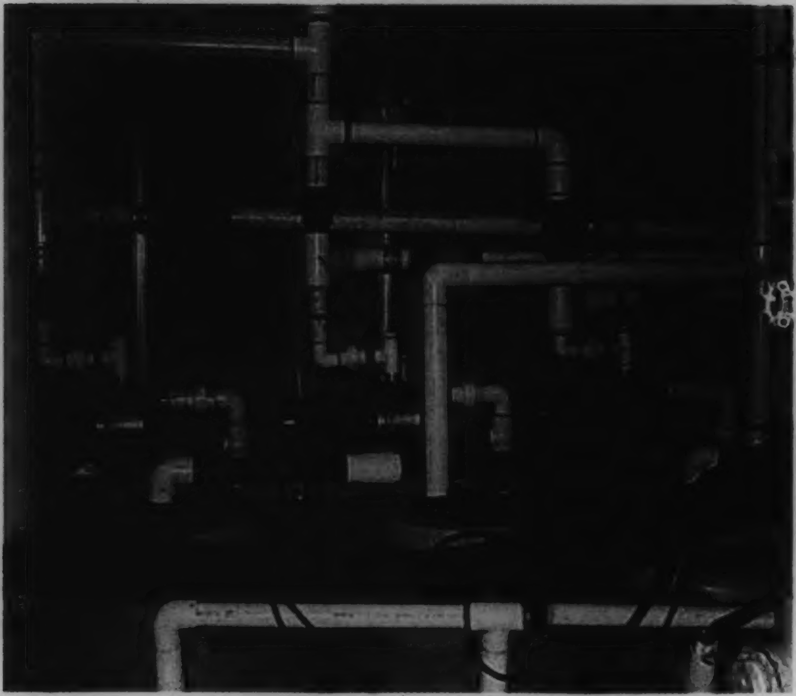

Figure 4.2.1 Ozonated water pumping system modifications

To increase the capacity of the ozone columns, the rotameter on contactor 1 and 2 (column A) was replaced with one that had a maximum capacity of 220 LPM (Figure 4.2.2). This, in combination with the other two ozone columns, provided adequate flow to the ozone storage tanks. However, when flows are over 110 LPM, water flows over the top of the contactors. The ozone columns are not sealed on the top. The outlet of contactor 1 is joined to the inlet of contactor 2 with a 38 mm pipe attached approximately 250 mm from the top of the first ozone column. Therefore, when flows are in excess of 110 LPM, backpressure causes the water to rise in column 1 and spill out of the top. Cutting a larger hole in the ozone column to allow more water to flow out of it is not appropriate, as the saddles that attach to the ozone columns are not available in outlet sizes greater than 38 mm.

Figure 4.2.2 Ozone column and rotameter

4.3 Experimental Design

The overall treatment process train did not change for the duration of the pilot testing period. An advanced treatment train was used with pre-ozonation of the water in hopes of improving coagulation and flocculation. Advanced treatment is the same as conventional treatment except DAF is used instead of sedimentation for clarification. A more detailed description of the process train and its individual unit processes is located in Section 4.1 and Appendix A.

As stated in Section 1.3, the primary objectives of the pilot study were to determine the operating conditions, and chemical doses that would best treat water from the Seymour water supply impoundment with the process train described above. Because of the number of variables that can affect the results, a factorial design based method of experimentation was chosen for this study. Each unit process needed to be optimized individually. Therefore, ozone and coagulation conditions were optimized first, followed by flocculation conditions and finally DAF operating conditions. Filters were run consistently for the length of the pilot study. Variables from a number of treatment units were used in one factorial design if interactions between different unit processes were to be studied. Following is a list of factors for each unit process, and their significance in the experimental design.

Ozonation:	Ozone Dose – Varied from 0 mg/L to 2.0 mg/L
	Ozone Contact time – Remained relatively constant at 4 to 7 minutes depending on flow
Coagulation:	Coagulants – Alum, Ferric Chloride and Polyaluminum chloride were tested at different times
	Mixing – Static mixers at a constant velocity gradient of approximately 2240 s^{-1} and retention time of approximately 2 to 3 seconds.
Flocculation:	Stages – 2 to 3 stages depending on the desired detention time
	Detention time – 8 to 15 minutes (changed by changing flow through unit and number of stages)
	Velocity gradient – Changes with changing paddle speed. Values varied between 27 and 122 s^{-1}
DAF:	Flow – controlled by the flow into the flocculation basin
	Retention time – controlled by the flow into the flocculation basin
	Scraper speed – Constant at 10% (approximately 1 r.p.m.)
	Saturator pressure – Constant at 480 +/- 80 kPa
	Recycle ratio – Varied between 8 and 20 percent
Filtration:	Loading rate – constant for each filter at 360, 310 and 372 litres per hour for filter 4, 5 and 10, respectively
	Media configuration – 300 mm of 0.7 mm sand overlain by 2400 mm of 1.4 mm anthracite in each filter for the duration of the pilot study.

Detailed descriptions on the techniques for process optimization are located in the results and analysis section. The section is divided into three parts, each representing one of the three coagulants tested. Experiments were normally based on 2^2, 3^2 or 2^3 factorial designs, however, one-variable-at-a-time experimental design methods were used to establish the levels in the factorial designs. One-variable-at-a-time methods were also used if the raw water quality changed over the course of a planned factorial design experiment. Sometimes only a couple runs could be performed before the raw water quality changed significantly. As a result, there were few complete factorial designs performed. Many of the conclusions will be based on results from one-variable-at-a-time analysis of the data. In addition, there were some sets of runs where two factors, such as coagulant dose and ozone dose, were varied at a number of levels. These runs will also be analyzed as if they were one-variable-at-a-time experiments.

Each run was performed in generally the same manner, irrespective of the levels or parameters being investigated. Normally, filters were backwashed before the start of the run. The equipment was checked to be sure that it functioned properly and that everything was set at the desired values as dictated by the experimental design. All of the experimental conditions were recorded on experimental run data sheets for each run performed. It was up to the experimenter to determine the length of each run. This decision was based on the objectives of the individual run, and the information that was required. If filter performance was the key variable being studied, then runs usually went on for more than 12 hours or until particle breakthrough occurred. If flocculation or DAF performance was being studied, then shorter run times could be performed, and filters may not have to be backwashed between each run. A minimum of six plant volumes of water was run through the entire process train before measurements were taken. This was to ensure that all the unit processes had stabilized, and that water affected by the previous runs had been removed. At a flow of 100 LPM, the total plant retention time is approximately 15 minutes. Therefore, the plant was run under consistent experimental conditions for a minimum of 1.5 hours before measurements were taken.

4.4 Analytical Procedures

Seven sampling ports located at different points in the process train were used to collect grab samples for laboratory testing of the chosen water quality parameters. Locations of the sample points are shown on the pilot plant schematic drawing, located at the end of Appendix A. A description of the sampling locations and their significance follows:

Sample point, r: Raw water samples were taken from a port located on the main 75 mm raw water feed line, at the point where the line entered the northwest end of the building. Samples from this location were representative of conditions in the impoundment, although some temperature change may have occurred as the water flowed from the impoundment to the pilot plant. In addition, water quality changes in the impoundment were not detected in the pilot plant for some time because of the transportation time between the impoundment and the pilot plant.

Sample point, o: This sampling location was not used extensively for this study except when samples for ozone residual analysis were needed. The port is located on the inlet pipe to the ozonated water storage tanks, after the ozone columns.

Sample point, c: The location of this port is between the static mixers and the DAF tank. This location was needed for determining the characteristics of the water entering the DAF/flocculation unit.

Sample point, d: This sample point was used for determining water quality characteristics of DAF effluent. The port was located on the DAF effluent pipe, outside the DAF tank, approximately 150 mm from the DAF outlet.

Sample points, 4f, 5f, 10f: An array of sample ports is located on a platform above the clear wells for sampling filtered water effluent for all filters in the pilot plant (Figure 4.4.1). Filter effluent samples were normally taken from just one port for each run, depending on the objective of the run.

Figure 4.4.1 Filter effluent sampling ports

A variety of water quality parameters were determined for each sample taken. Turbidity and particle count data were used to analyze the removal of suspended matter. TOC, DOC, UV_{254}, and colour were determined as indicators of the type and quantity of organic matter in the raw and treated water. Temperature, pH, and ozone residual are the other water quality parameters that were regularly tested. Below are detailed descriptions of the water quality parameters tested, and the methods used to determine their quantities.

Turbidity. Turbidity measurements were made in accordance with Standard Method 2130 (SM2130). The measurement is based on a comparison of the measurement of light scattered through a sample by suspended material and the light scatter in a standard sample. Grab samples were analyzed on a HACH 2100N turbidity meter with an LED display. The 2100N was calibrated at the beginning of the study, and was checked daily against the online turbidity meters and the turbidity meter located in the chlorine building. Online turbidity meters, model HACH 1720C, were located in the process train to record continuous raw water and filter effluent turbidities (Figure

4.4.2). These meters were cleaned weekly and checked daily against the 2100N in the lab, and the turbidity meter in the chlorine building. No calibration was necessary for the duration of the study.

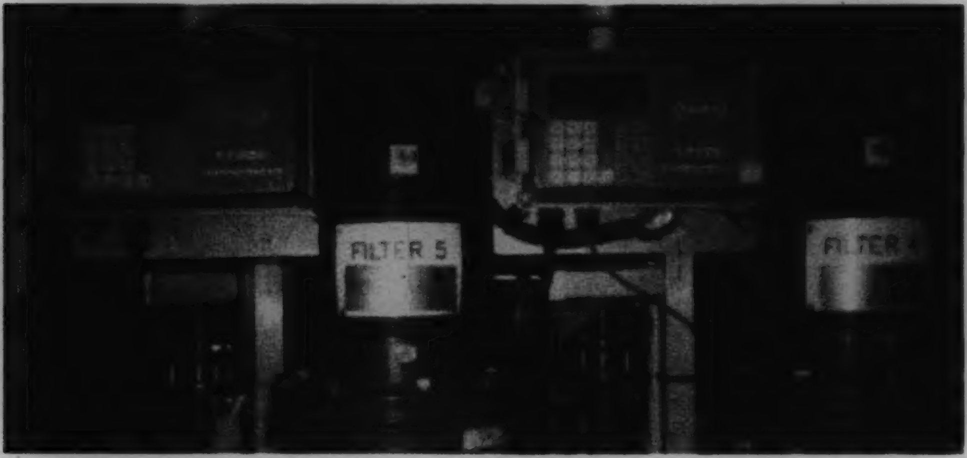

Figure 4.4.2 Online turbidity meters

Particle Counts. Grab samples were measured using a potable water sensor manufactured by L & H Environmental Inc., and assembled at the University of Alberta (Figure 4.4.3). The design of the water particle sensor is based on a laser light blocking principle (SM2560C), and provides particle count data over a size range of 2 to 200 microns. Size ranges can be deliminated as the experimenter sees fit. Sample flows are maintained at 60 mL/min, and no field calibration is required. Results are presented and analyzed on a spreadsheet program.

Figure 4.4.3 Potable water sensor and computer

One online Met One Model 215W particle sensor was used to analyze raw water, and the other recorded filter effluent data. The sensors, similar to the bench top model, are based on a laser light blocking principle. The size range of the sensors is 2 to 750 microns. Pre-programmed sized ranges were different from those of the bench model. Online particle sensors were cleaned daily.

Temperature. Temperature measurements were performed with a mercury glass thermometer, with markings every 0.1 °C.

pH. The pH of samples were determined using an Orion 420A pH meter. The pH probes were filled with a potassium chloride solution at the beginning of the study period and refilled in the middle of the study. Buffer solutions were replaced every month and the pH meter calibrated every morning. Online pH meters were available in the pilot plant, but not used for this study.

Colour. Colour was determined using the Visual Comparison Method (SM2120B). Only apparent colour, colour due to substances in solution and suspended matter, was determined for the purposes of this study. Most of the samples had low turbidity, therefore turbidity interferences should have been minimized. Platinum cobalt standard solutions were prepared by a technician at the University of Alberta with colors of 5, 10, 30, 60, and 80 color units. Standards and samples were stored in 50 mL coloured nessler tubes, which were kept in a refrigerator. The pH of the samples was adjusted to values between 7.4 and 7.6 using concentrated sodium hydroxide (NaOH) solution.

Ozone Residual. Ozone residual measurements were performed using a HACH DR100 colorimeter and ozone reagent ampoules. This method is based on the Standard Method's Indigo Colorimetric Method (SM4500-O_3). HACH AccuVac Indigo Ozone Reagent ampoules come in low range (0.00 to 0.25 mg/L O_3) or mid range (0.00 to 0.75 mg/L O_3) concentrations. To perform the test, the tip of an ampoule is broken off in an ozonated water sample. The water enters the ampoule and mixes with the indigo solution. Since ozone decolorizes indigo, the concentration can be measured by the colorimeter based on the difference in colour from an ozonated sample, and a standard sample that is free of ozone.

UV_{254}. The amounts of UV-absorbing organic constituents were determined based on the Standard Method's Ultraviolet Absorption Method (SM5910B). Historically, a wavelength of 254 nanometers (nm) has been chosen, but that selection was arbitrary. It is up to the experimenter to choose a wavelength that is appropriate for the test being conducted. A wavelength of 254 nm was used in this study. Turbidity interferences were removed by filtration through Whatman 934-AH glass microfibre filters. Absorbency was measured using a Milton Roy Company Spectronic 601 Spectrophotometer (Figure 4.4.4).

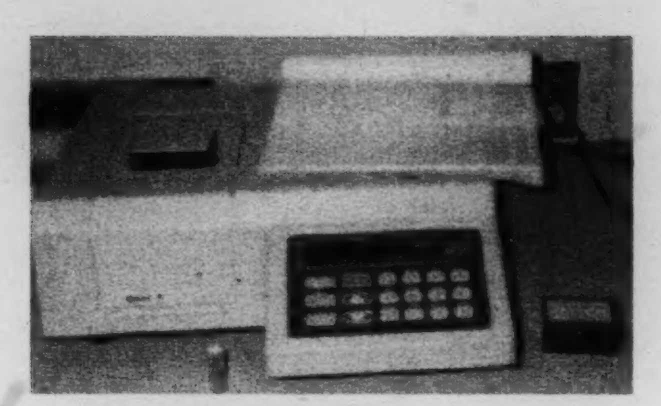

Figure 4.4.4 Spectrophotometer

TOC and DOC. Because of limited resources, total organic carbon and dissolved organic carbon could not be determined in this study. Instead, based on a comparison of data from previous pilot plant studies at this facility, TOC and DOC were determined from UV_{254} results. A discussion of the validity and practice of this procedure was presented in Section 2.5.

4.5 Bench Scale Experiments

Very few bench-scale experiments were run over the course of the pilot plant study. Jar testing was attempted to see the effects of different coagulant and ozone doses on raw water. However, as expected, the floc did not settle in a reasonable amount of time and the results were discarded. Some jar-test experiments on the effects of powdered activated carbon on removal of organic matter in water were attempted, but the same problem was encountered with that of the coagulation/flocculation jar test experiments.

Successful jar tests experiments were performed to determine the effects of different soda ash concentrations on the pH of raw water. The same raw water was placed into five jars (the sixth jar did not have a paddle) and were mixed at a high rpm. Different concentrations of soda ash were then added, and the final pH determined. The results are shown below in Table 4.5.1.

Table 4.5.1 Soda Ash bench experiments

Concentration of Na_2CO_3 (mg/L)	Raw Water pH (pH units)	Final pH (pH units)
1	6.4	7.0
2	6.3	6.9
3	6.4	7.3
5	(6.1)	7.5
7	6.4	9.2

The reading for the raw water pH for jar 4 is suspect, and thus has been bracketed. These results helped determine the amount of soda ash required to be added to the water to maintain a constant pH for coagulation. The amount of soda ash required for each specific run was mostly determined by the type and amount of coagulant used, and was determined at the pilot scale.

5.0 Results and Analysis

5.1 Alum

5.1.1 Experimental Conditions

Alum is the most common chemical coagulant used for the destabilization of colloidal particles in drinking water treatment applications. It has also been previously shown to work well in combination with ozone, (Johnson, *et al.*, 1995), and was thus used for the greatest amount of time in this study relative to PACl and $FeCl_3$ testing. Phase 1 alum testing took place between July 26 and September 23 during a period of consistent raw water quality with low turbidity and organic material, and high water temperatures. Phase II alum testing occurred between October 19 and November 18. This testing period coincided with a major turbidity event that started at the end of October.

Alum is the common name for aluminum sulfate, ($Al_2(SO_4)_3$). It, like PACl, is an aluminum based metal salt that, when added to water, will hydrolyze and form aluminum hydroxide precipitates when the pH is between 4 and 12, (Reynolds, *et al.*, 1996). Because alum consumes three hydroxide ions for every aluminum ion released into solution (refer to Section 2.2), alkalinity is required. If the alkalinity is not naturally occurring in the water, such as the case in the Seymour Reservoir, lime or soda ash mush be added at the time of coagulant addition to control the pH. Otherwise, precipitation may not occur, and the treated water quality may not meet "Canadian Drinking Water Quality Guidelines" for pH (6.5 to 8.5), (Health Canada, 1996).

The alum used for this study was delivered in the liquid form. Solid alum is also available as a powder, granule or lump. The alum was shipped in 27 kilogram pales by PrarieChem Ltd of Richmond, BC. It is a pure substance that is clear with a pale straw or greenish-blue colour. Its specific gravity is 1.333 at 15.6°C and it is normally shipped at a concentration of 49 percent. It is very soluble in water and therefore it does not need continuous mixing to keep it homogenous. Specific details on coagulant preparation are located in Appendix A. Throughout the study, alum concentrations were expressed as mg/L of $Al_2(SO_4)_3$, not, as commonly done, as mg/L of Al^{3+}.

Figures 3.2.1 through 3.2.6 in Section 3.2 show raw water characteristics for the pilot plant study period. The data taken at the lab to produce those figures have been condensed and are located in Table C1 in Appendix C. Turbidity, temperature, pH, UV-absorbance at 254 nm, colour and particle counts were the water quality parameters used for this study. Colour analysis did not start until October 1, and UV_{254} analysis did not start until September 14. Alum testing occurred in two phases. The first testing period took place between July 26 and September 23 and the second testing period occurred between October 19 and November 18. Phase 1 testing took place during a fairly dry period in Vancouver, although air temperatures were below average for that time of year. Because of these meteorological conditions, particle count and turbidity values were relatively constant. There was one small increase in suspended particle matter that commenced on September 8. This event occurred after the water was turned on after a two week plant shutdown between August 24 and September 8. On September 8, when the water was turned back on, the water scoured the pipes and flushed out sediments that had been deposited there during the shut down. This created a brief turbidity event not consistent with impoundment water conditions. Turbidity and particle counts returned to summer values by September 18, or just over a week later. Samples for colour analysis were not collected during this phase of the testing, so the amount of organic matter in the water had to be gauged using UV-absorbance as the only parameter. Some of the values for UV-absorbance tested between September 14 and September 28 were mistakenly done using unmatched cuvettes, and therefore there may be some erroneous results in this time period. Temperature readings rose consistently from a value of 9.9°C on July 26 to 13.2°C on September 23.

Phase 2 alum testing occurred between October 19 and November 18. Shortly after testing began, a turbidity event occurred, which elevated the turbidity from 0.40 NTU to 2.29 NTU by November 16. Total particles greater than 2 μm in diameter rose by 800 percent in this time period. The amount of organic matter as measured by UV-absorbance rose from 0.075 cm^{-1} to 0.127 cm^{-1}. Colour rose by 17 apparent colour units to 34 ACU. Temperatures during this time period continued to fall from approximately 11.0 °C to 7.0 °C by the time alum testing was completed on November 18. As will be seen in later sections, temperature can play an important role in the performance of coagulants, particularly alum. Table 5.1.1 below, summarizes raw water quality ranges at the beginning and end of each testing period. Also included are maximum values encountered during those periods.

Table 5.1.1 Raw water characteristic for alum testing

	Period	
	July 26 to September 23	October 19 to November 18
Turbidity (NTU)	0.26 to 0.30 (0.59 max.)	0.40 to 2.11 (2.29 max.)
Particles, >2 µm (#/mL)	468 to 392 (1220 max.)	771 to 4613 (5238 max.)
Particles, >4 µm (#/mL)	210 to 196	393 to 2322
Particles, >8 µm (#/mL)	60 to 65	128 to 636
Particles, >16 µm (#/mL)	0 to 1	1 to 2
Particles, >32 µm (#/mL)	0	0
Particles, >50 µm (#/mL)	0	0
Colour (ACU)	-	26 to 28
UV_{254} (cm^{-1})	0.071 at end	0.084 to 0.112
Temperature (°C)	9.9 to 13.2	10.6 to 7.5

Some equipment and operating problems were encountered when alum testing was occurring. Between October 25 and November 23, the lamp on the high concentration (HC) ozone monitor was burnt out and no readings were displayed. This coincided with the high turbidity event, when the turbidity hit a peak of 2.29 NTU on November 16. As will be seen in Section 5.1.3, the alum dose was never properly stabilized for this event. No other major equipment malfunctions occurred during alum testing. Small problems at the pilot plant occurred continually, however, these were noted and usually fixed at the time they occurred. Some of these problems included leaky coagulant dosing tubes, debris stuck in the rotameters and blown circuits for the ozone generator and flocculator mixing paddles. At times, the DAF saturator did not maintain a constant pressure or flow. Most often, over the course of a few days, the pressure in the saturator would slowly decrease. To keep the pressure at acceptable values, the flow into the saturator would have to be increased. This, however, increased the recycle ratio. As a result, the saturator had to be stopped every few days so that the settings could be reestablished.

5.1.2 Experimental Design Description

It is popular to use a factorial design method of experimental design, rather than the more simple one-variable-at-a-time method. One-variable-at-a-time methods are very simple to plan and perform, however they ignore interactions among experimental variables. The one-variable-at-a-time method estimates the effect on a response variable by changing one parameter, when all other parameters are fixed. It assumes this effect is the same at all other conditions of the other parameters being tested, (Box, *et al.*, 1978). In others words, the variables respond additively. Factorial designs not only handle variables that act additively with more efficiently, but they can detect and estimate the interactions that do not act additively. They quantify the significance of each main effect (change in response of one variable over all of the other variables), as well as the interaction effects. In addition, they help determine appropriate levels, or values that parameters are set, for future experimentation. Factorial designs are also useful for developing simple linear and non-linear models.

There are some disadvantages and limitations with factorial designs. Although they measure the significance of each parameter with respect to their effect on a response variable, their significance may be misleading depending on the choice of the levels that they are tested at. Perhaps the biggest disadvantage in relation to using factorial designs for pilot plant work is that the control parameters must remain constant for the results to be meaningful. In the case of the Seymour pilot plant study, raw water conditions have to be consistent throughout the complete factorial design. If not, changes in responses could be due to changing raw water conditions and not the change in testing conditions for the parameters. For the purposes of this study, factorial designs were used and analyzed as such when possible. Otherwise, runs were performed one at a time, and graphical and others analysis methods were used to evaluate the data.

Table C2 in Appendix C summarizes run information for each run performed with alum as the coagulant. The table includes run number, start time, ozonation conditions, coagulation conditions, flocculation conditions, DAF conditions and filtration conditions. Each one of these runs will be described in more detail. They have been broken down into smaller groups as follows.

Test runs 0729c to 0820r

Because the pilot plant had not been operational for over a year before this study was started, it needed to be run for some time for it to stabilize. This period of initialization also provided time to determine problems with the plant and make modifications. These modifications were discussed in Section 4.2. There were therefore four objectives for performing runs 0729c to 0820r:

(1) gain experience running a pilot plant;
(2) determine maintenance and modification needs;
(3) evaluate coagulant and ozone doses for future experimentation; and
(4) establish filtration rates to be used for the duration of the study.

Because there was very little prior knowledge on the interaction of ozone and alum for use as coagulants on Seymour impoundment water, a wide range of values was explored for this initial testing stage. Filtration rates were explored briefly, and based on these runs and recommendations from earlier operators at the pilot plant, filter loading rates were set at 360, 310 and 272 L/hr for filter 4, 5 and 10, respectively. Experiments run during this phase are summarized in Table 5.1.2, below. All parameters except alum and ozone dose remained constant. Refer to Table C2 in Appendix C for these data.

Table 5.1.2 Experimental runs 0729c to 0820r

	Ozone dose (mg/L)			
Alum dose (mg/L)	0	0.5	1	2
4	0810j		0805f, 0806g, 0810k	
6	0817n	0817m		
8	0809i	0818o	0804d, 0805e, 0809h, 0811l	
10	0820r	0818p	0819q	0729c

Some runs were repeated because of malfunctioning equipment or lack of data taken in the first trial. Flocculation and DAF operating conditions were held constant for these runs. Flow into the flocculation tanks was steady at 80 LPM, with flocculation velocity gradients set at 30 s^{-1}. Average DAF operating conditions during this time period are summarized in Table 5.1.3 below. Because of the nature of the saturation equipment, some drifts in recycle flow and saturator pressure are expected to occur. This drift is slightly higher than usual for these initial experiments because of plant start-up and operator inexperience.

Table 5.1.3 DAF operating conditions during runs 0729c to 0820r

	Operational Parameter			
	Recycle Ratio (%)	Saturator Pressure (kPa)	Scraper Speed (%)	Loading Rate (m/hr)
Average	11.8	430	10	6.9
Standard Deviation	0.6	20	0	0
Maximum Value	12	460	10	6.9
Minimum Value	10	380	10	6.9

Test runs 0908w to 0916ai

Table 5.1.4 shows a 2^3 factorial design (3 parameters tested at two levels each, positive and negative, with a center point replicate) with flow (DAF loading rate) alum dose and ozone dose as the parameters.

Table 5.1.4 Experimental Design, runs 0908w to 0916ai

	LEVELS		
	(-)	Center Point	(+)
Flow (LPM), A	100	90	80
Alum (mg/L), B	10	7	4
Ozone (mg/L), C	0.5	0.25	0

Runs corresponding to the above factorial design are located below in Table 5.1.5.

Table 5.1.5 Factorial design information for runs 0908w to 0916ai

	Factor		
	A	B	C
0910z	-	+	-
0912aa	-	+	+
0913ab	-	-	-
0913ac	-	-	+
0915af	+	+	-
0915ag	+	-	-
0916ah	+	-	+
0916ai		Center Points	

The final run to test the ABC interaction (all levels positive) was not performed. The pump that delivers soda ash to the static mixers was not operational between September 10 and September 14. Therefore, the pH of the water after coagulation for runs 0910z and 0912aa was 5.0 to 5.2. The alum dose for these runs was 10.0 mg/L. The pH of the water for runs 0913ab, 0913ac and 0914ad was between 6.2 and 6.4. The pH was higher for these runs because the alum dose was only 4.0 mg/L. As will be seen in the proceeding section, DAF effluent for all runs with alum doses of 4.0 mg/L are poor, regardless of the pH. Additional runs, 0908w, 0909x, 0909y, 0912aa, 0914ad, 0914ae, were performed as repetitions or miscellaneous runs to gain more information on ozone and alum interactions. For example, runs 0909y, 0914ad and 0914ae used higher ozone doses than previously tested. Runs 0908w and 0909x were performed to re-establish ozone and alum doses after a brief plant shutdown.

Test runs 0917aj to 0923aq

Runs 0917aj to 0922ap formed part of an incomplete factorial design as shown in Table 5.1.6.

Table 5.1.6 Experimental Design, runs 0917aj to 0923aq

	LEVELS		
	(-)	Center Point	(+)
Flow (LPM), A	100	90	80
Stages (#), B	3	-	2
G (s^{-1}),C	30	65	100

Runs corresponding to the above factorial design are located below in Table 5.1.7.

Table 5.1.7 Factorial design information for runs 0917aj to 0923aq

	Factor		
	A	B	C
0917aj	-	+	-
0920ak	-	-	+
0920al	-	+	+
0921am	+	+	+
0921an	+	-	+
0922ao	+	+	-

Run A (flow = 80 LPM; 3 stages; G = 30 s^{-1}) and run 1, all levels negative (flow = 100 LPM; 3 stages; G = 30 s^{-1}) were not performed. Run 0922ap was a repeat of run 0920ak, but was run overnight to investigate long-term filter performance. All these runs were performed to gain an understanding of the effects of flocculation conditions (velocity gradient, number of stages, loading rate) on the performance of the DAF process. The runs were all performed at an alum dose of 7.0 mg/L and an ozone dose of approximately 0.30 mg/L.

Test runs 1019bl to 1029bx

The final runs for alum were performed later in the year, from the middle of October to the middle of November. At this time, the turbidity of the water was beginning to increase due to heavy rainfall in the Seymour valley. From October 19 to October 29, the turbidity increased from 0.39 NTU to 0.66 NTU. There was also a corresponding increase in the number of suspended particles. The temperature of the water dropped from 10.9 °C to 9.1 °C. In addition, colour and UV-absorbance were measured for these runs, which was not the case for most of the previous alum runs. This allowed the experimenters to gain an understanding on the effects of ozone and the DAF unit on the removal of organic matter. In addition, experimenters desired to investigate the effects of changing raw water conditions on optimum coagulant dose and coagulant-ozone interactions. An increase in turbidity resulted in a corresponding increase in organic matter. Because there may be a critical concentration of NOM for ozone to be effective (refer to Section 2.4), more runs on ozone and coagulant interactions were performed with water at higher turbidities. A summary of the runs performed for this purpose is shown below in Table 5.1.8. Only ozone dose and alum doses were varied. All other parameters remained constant.

Table 5.1.8 Experimental Conditions, runs1019bl to 1029bx

	Alum Dose (mg/L)			
Ozone Dose	4	7	10	15
0	1019bm	1028bu	1019bl	1020bn
0.25	1021bq	1023bs	1020bo	1023br
0.5	1025bt	1028bv	1021bp	1029bx
1		1029bw		

Test runs 1103by to 1118cu

The first and only major turbidity event of the pilot study period occurred between October 28 and November 16, where the turbidity rose to a maximum value of 2.30 NTU. This event provided a good opportunity to investigate the effects of alum dose and ozone on raw water with higher than average particles and organic matter.

However, none of the dosing combinations performed during this period produced a suitable floc in the DAF unit, resulting in poor filter effluent turbidity. This was attributed to the following:

(1) duration of the turbidity event – only two weeks were available to test high turbidities and this time was not adequate to establish a proper alum dose;
(2) equipment failures – saturator was producing poor bubbles; and
(3) improper alum dose – no floc in the DAF tank could be established before the turbidity started to decrease. Higher alum doses should have been attempted earlier on.

5.1.3 Presentation of Results

A table of results for all runs including alum is located in Appendix C, labeled Table C3. Detailed discussions on the results of alum testing are located in the following sections. Runs are grouped in the same manner as in Section 5.1.2.

Test runs 0729c to 0820r

Table 5.1.9 below, shows DAF performance results for the runs 0729c through 0820r.

Table 5.1.9 DAF performance, runs 0729c to 0820r

	Parameter				
Treatment Combination	DAF turbidity reduction (%)	DAF Turbidity (NTU)	DAF particle reduction, >2 µm (%)	DAF particle reduction, >4 µm (%)	DAF particle reduction, >8 µm (%)
0729c	-	0.67	-	-	-
0804d	-	-	-	-	-
0805e	0	0.50	15	12	17
0809h	-50	1.21	-12	-4	-5
0809i	64	0.22	59	56	51
0810j	-28	0.48	-40	-24	-12
0810k	-11	0.32	15	22	33
0811l	-24	0.58	-15	-1	16
0817m	23	0.53	-5	4	-1
0817n	12	0.68	1	9	10
0818o	37	0.50	18	29	30
0818p	53	0.36	41	49	55
0819q	36	0.53	9	34	37
0820r	67	0.22	78	81	81

No measurements for runs 0805f and 0806g were taken because of pilot plant operational problems. Data for DAF particle reduction for particles greater than 16 µm are not included. This is because the number of particles in the raw water in these size ranges is very low, and therefore values for percent reduction in the DAF tank may be erroneous or misleading. As stated earlier, no measures of the organic content of these samples in terms of UV-absorbance or colour were taken.

Runs 0809i, 0818p and 0820r produced DAF effluent with the highest turbidity and particle count reductions. Alum doses for these runs were 8.0, 10.0 and 10.0 mg/L respectively. Ozone doses were 0.00, 0.50 and 0.00 mg/L, respectively. Runs using alum doses of 4.0 mg/L and 6.0 mg/L did not produce a floc and therefore particle removal in the DAF unit was poor. In addition, when ozone doses of 0.5 mg/L (except when with an alum dose of 10.0 mg/L) and higher were used, floc formation appeared to be hindered. Along with poor particle reduction rates in the DAF unit, poor floc formation can be seen by the lack of dark scum on the surface of the flotation tank. Figures 5.1.1 and 5.1.2 compare runs with good scum and bad scum. More detailed particle analysis and analysis on the effects of ozone on coagulant are located in Section 5.1.4 and 5.4.5.

Figure 5.1.1 Good DAF scum layer

Figure 5.1.2 Poor DAF scum layer

Test runs 0908w to 0916ai

Table 5.1.10 displays results for the factorial design described for this group of runs. The first part of the table deals with runs included in the factorial design described in Section 5.1.2. As indicated in that section, the run that tested interaction ABC was not performed. Higher order interactions tend not to be significant, however, factorial design analyses can not be completed without those missing data. The second part of Table 5.1.10 shows results from runs not included in the original factorial design. Runs 0908w, 0909x, 0909y were used to re-establish doses after a period of down time at the pilot plant. Runs 0914ad and 0914ae tested higher ozone doses (1.0 mg/L) with alum doses of 4.0 mg/L and 10.0 mg/L, respectively.

Table 5.1.10 DAF performance, runs 0908w to 0916ai

	Parameter				
Treatment Combination	DAF turbidity reduction (%)	DAF Turbidity (NTU)	DAF particle reduction, >2 µm (%)	DAF particle reduction, >4 µm (%)	DAF particle reduction, >8 µm (%)
0913ab	35.5	0.62	50	48	44
0915ag	-9.0	0.66	-13	-12	0
0910z	5.1	0.88	41	36	30
0915af	62.9	0.35	83	85	88
0913ac	25.3	0.57	27	38	36
0916ah	-2.4	0.52	1	-7	1
0912aa	-1.3	0.71	38	45	49
0916ai	66.9	0.27	80	80	72
0908w	75.3	0.25	81	81	77
0909x	64.1	0.42	66	67	59
0909y	56.8	0.44	59	61	62
0914ad	-7.1	0.64	-22	-19	-18
0914ae	59.6	0.35	64	67	67

Similar to results in the last grouping of runs tests, runs with alum doses of 10.0 mg/L and no ozone produced the best results (refer to run 0915af). Run 0915af was performed at a flowrate of 100 LPM. With these data, it is clear that at any particular raw water quality, coagulant dose is very important. The center point replicate run (0916ai) also resulted in very good DAF effluent quality. The only difference between run 0915af and 0910z were the flowrates (100 LPM and 80 LPM, respectively). However, DAF effluent quality for run 0910z was much poorer because there was no pH adjustment. The only difference between runs 0912aa and 0909x was that run 0909x had its pH adjusted and was performed when the raw water quality was slightly poorer (0.55 NTU versus 0.43 NTU). When no soda ash was added, proper flocculation did not occur because aluminum hydroxide precipitates were not able to form. Therefore, DAF efficiency was low with respect to suspended solids removal. Runs 0913ab through 0914ad also had no pH adjustment and therefore had poor DAF effluent quality. However, alum doses were 4.0 mg/L and 10.0 mg/L respectively. Results indicate that in this case, with no soda ash adjustment, the run with an alum dose of 4.0 mg/L produced better results than run 0914ad, which had a dose of 10.0 mg/L. With lower alum dose, the pH does not decrease as much, and therefore aluminum hydroxide precipitates will form more easily. Still though, runs with an alum dose of 10.0 mg/L and proper soda ash adjustment work best. Run 0913ab had no ozone added, run 0913ac had 0.54 mg/L of ozone added, and run 0914ad had 1.32 mg/L added. Again, it is clear that as the ozone dose increases, particles have less of a tendency to flocculate. The alum dose for all three of these runs was 4.0 mg/L. Runs 0908w, 0909x and 0909y were performed on raw water that had a slightly higher turbidity (0.55 to 0.59 NTU) than had been previously seen. Alum doses were 8.0 mg/L, 10.0 mg/L and 10.0 mg/L, respectively. Ozone doses were 0.48 mg/L, 0.62, mg/L and 0.92 mg/L, respectfully. Referring to Table 5.1.3.2, turbidity and particle reductions in the DAF unit were quite good, with turbidity reductions ranging from 75% to 57 %. Again, as the ozone dose was increased, the efficiency of the DAF unit for removed suspended particles also decreased. More detailed discussions on the effects of ozone on DAF particle removal are located in Section 5.1.4.

0917aj to 0923aq

Table 5.1.11 on the following page shows results for the factorial design for runs 0917aj to 0923aq, and previously described in Section 5.1.2. As noted in that section, two runs that were a part of this design were not performed. Also included in Table 5.1.11 are runs 0922ap and 0923aq, which were performed shortly after the runs for the factorial design. The factorial design studied the effects of flocculation operating conditions on DAF performance, particular for removing suspended particles. In addition, UV-absorbance measurements were taken for the first time.

Table 5.1.11 DAF performance, runs 0917aj to 0923aq

Treatment Combination	B (0917aj)	AB (0922ao)	C (0920ak)	AC (0921an)	BC (0920al)	ABC (0921am)	0922ap	0923aq
DAF turbidity reduction (%)	37	66	61	63	57	63	67	62
DAF turbidity (NTU)	0.50	0.27	0.29	0.26	0.30	0.28	0.24	0.25
DAF particle reduction, >2 µm (%)	71	73	61	28	54	60	82	56
DAF particle reduction, >4 µm (%)	75	75	71	44	57	63	84	59
DAF particle reduction, >8 µm (%)	80	76	72	54	64	71	83	56
UV_{254} removal after coagulation (%)	61.1	-	48.7	-	-	67.9	-	-
DAF UV_{254} removal (%)	-3.7	-	13.0	-	-	7.1	17.2	-
Post-DAF UV_{254} (cm^{-1})	0.028	-	0.020	-	-	0.026	0.024	-

*main effect A and interaction (-) were not performed

All the preceding runs were performed at an alum dose of 7.0 mg/L and an ozone dose of 0.25 mg/L, with the exception of run 0923aq, which used an ozone dose of 0.50 mg/L. Raw water conditions were consistent throughout this set of runs, with turbidity ranging from 0.30 to 0.32 NTU. It is apparent from these data that once a suitable coagulant dose is established, the flocculation of particles is robust with respect to flocculation tank operating conditions. DAF turbidity removals, with the exception of run 0917aj, were all above 57 percent. It is not known why DAF turbidity removal for run 0917aj was only 37 percent when DAF particle removal, was 71 percent. Particle reduction in the DAF unit, for particles greater than 2 μm in diameter, was greater than 54 percent for all runs, with the exception of run 0921an, which had a particle removal efficiency of 28 percent. Similarly, it is not know why DAF particle removal for run 0921an was so poor when turbidity removal for the same run was 63 percent. Grab samples for turbidity and particle analysis were collected at the same time, but in separate containers. It is possible that one of the containers was dirty when these samples were taken.

UV-absorbance analyses were performed for the first time for this set of runs. Percentage reductions for the few samples taken ranged from 49 to 68 percent. These removal rates are for samples taken before the DAF unit, but after coagulant addition (i.e. with respect to raw water UV-absorbance). These results indicate that most of the UV-absorbing organic matter in the water is removed via adsorption onto chemical precipitates immediately following chemical injection. The DAF unit acts as a polishing step. Samples for colour analysis were not taken at the time of these experiments.

There is very little difference in the quality of the DAF effluent when flocculator mixing intensity or detention times are changed within reasonable boundaries. This indicates that lower flocculation tank detention times can be used at full scale. This results in cost savings in terms of the space required for flocculators, and quantity of water that can be produced. In addition, lower mixing intensities can be used, which reduces power consumption.

Test runs 1019bl to 1029bx

Results for runs 1019bl to 1029bx are located on the following page, in Table 5.1.12. Only alum and ozone doses were varied for this set of runs. Flocculation and DAF operating conditions remained constant. Raw water quality slowly deteriorated during the testing period. Raw water turbidity increased from 0.40 NTU on October 19 to 0.66 NTU on October 29. It appears that the alum dose is the most important factor for achieving high quality water in the DAF effluent. Alum doses of 4.0 mg/L and 15.0 mg/L produced water in the DAF effluent that had higher turbidities than what entered. The exception was run 1025bt where turbidity removal was 34 % when an alum dose of 4.0 mg/L and an ozone dose of approximately 0.5 mg/L were used. However, the raw water turbidity was the lowest on October 25 for the period between October 19 and October 29. Alum doses of 7.0 mg/L and 10.0 mg/L produced the best floc in the DAF unit. Turbidity removal percentages for all runs using 7.0 or 10.0 mg/L of alum were higher than 50 %. Runs 1019bl, 1020bo and 1021bp used an alum dose of 10.0 mg/L and ozone doses of 0.0, 0.25 and 0.5 mg/L respectively. There was very little change in DAF effluent quality between these three runs, and if anything, the quality increased slightly with higher ozone doses. Section 5.1.5 will further discuss the effects of ozone on these runs. If runs 1028bu, 1028bv and 1029bw are compared, similar results are seen. These data are the first evidence of increased particle removal with pre-ozonation. The alum dose for these runs was 7.0 mg/L with ozone doses of 0.0, 0.5 and 1.0 mg/L, respectively. Again, there is very little difference between DAF effluent qualities for ozone doses of 0.0 and 0.5 mg/L. When an ozone dose of 1.0 mg/L was used, DAF effluent turbidity was slightly poorer. These results indicate that with small ozone doses, particle reduction in the DAF unit is slightly improved when treating water with slightly higher turbidities than earlier. These data may also indicate a relationship between the amount of NOM in the water and the effectiveness of ozone as a coagulant aid.

Table 5.1.12 Results, runs 1019bl to 1029x

Treatment Combination	1019bl	1019bm	1020bn	1020bo	1021bp	1021bq	1023br	1023bs	1025bt	1028bu	1028bv	1028bw	1029bx
Alum dose (mg/L)	10.0	4.0	15.0	10.0	10.0	4.0	15.0	7.0	4.0	7.0	7.0	7.0	15.0
Ozone dose (mg/L)	0	0	0	0.23	0.49	0.25	0.24	0.24	0.5*	0.00	0.5*	1.0*	0.5*
DAF turbidity reduction (%)	62	-7	-28	70	65	-3	-15	63	34	52	57	53	-46
DAF turbidity	0.53	0.79	1.60	0.33	0.40	0.79	1.32	0.40	0.66	0.53	0.43	0.59	1.62
DAF particle reduction, >2 µm	73	-	49	77	78	-	10	72	51	33	63	55	-6
DAF particle reduction, >4 µm	74	-	49	80	81	-	0	72	60	44	71	61	2
DAF particle reduction, >8 µm	75	-	42	80	82	-	-17	74	67	40	72	64	7
UV_{254} removal after coagulation (%)	82	54	89	93	94	73	73	93	69	92	92	96	85
DAF UV_{254} removal (cm^{-1})	0.001	0.005	0.001	0.001	0.000	0.006	0.012	0.001	0.001	-0.002	-0.002	-0.005	0.004
Post-DAF UV_{254} (cm^{-1})	0.014	0.034	0.007	0.004	0.004	0.013	0.008	0.004	0.016	0.008	0.008	0.008	0.008

* Ozone dose estimated because of burned out bulb in ozone meter

Removal of organic matter as measured by UV-absorbance at a wavelength of 254 nm appears to be positively affected by ozone dose. However, more important, is the alum dose. When turbidity removal in the DAF tank was greater than 50% (indicating an optimized alum dose), UV_{254} removal after coagulation averaged 92 percent. When turbidity removal in the DAF tank was less than 50 %, UV_{254} removal after coagulation averaged 74 %. Very little reduction in UV-absorbance occurred in the DAF unit. These results indicate that nearly all of the UV absorbing organic matter in the water is removed via adsorption processes onto coagulant products and not by precipitation or attachment onto floc particles in the DAF unit. Results indicate that ozone slightly improves organic matter removal before the DAF unit by processes described in Section 2.3.2. Perhaps even more significant is that ozone maintains good NOM removal even when particle flocculation is hindered by ozone addition. Therefore, indications are that a balance between particle removal and organic removal is required when determining suitable ozone doses.

5.1.4 Particle Size Distribution Diagrams

Particle size distribution information can be conveniently summarized by using particle size distribution (PSD) diagrams (SM2560A). The number, surface area or volume concentration of particles is plotted on the y-axis and the particle size ranges are plotted on the x-axis. An analysis of particle size distribution diagrams can lead to insight on the characteristics of particles, the effects of different flocculation conditions on them and their potential for forming floatable or settable floc. These may be indicated by a shift in the particle size distribution, or the removal of one particular size range of particle. Particle size ranges used for this study were chosen based on typical *Cryptosporidium* spp and *Giardia lamblia* sizes. Removal of other organisms such as bacteria and protozoa may also be judged by particle removal.

For the purposes of this analysis, number concentration and volume concentration diagrams have been chosen to explain particle behavior in this system. Four independent variables, ozone dose, coagulant dose, DAF loading rate and flocculator velocity gradient, were analyzed to determine their effect on particle size distributions. Each of these variables has been plotted on separate diagrams. On each diagram are particle size distributions for four sampling points in the treatment train; raw water, post-coagulation, post-DAF and post filtration, if data are available. The purpose for this arrangement is to detect changes in particle size distributions at different points in the treatment train, at the same time comparing different treatment processes on particle behavior. Of particular interest is determining if there is a shift to larger sized particles after coagulation, and a decrease or increase in particle concentrations after the DAF unit.

Appendix D contains 10 particle size distribution diagrams for the alum phase of the study. Five of the diagrams are for number concentration (labeled D1 to D5) and five are for volume concentration (labeled D6 to D10). Table 5.1.13 below details these labels.

Table 5.1.13 PSD diagram labeling

	Figure #	Parameter studied
Particle number distribution	D1	Ozone dose
	D2	Ozone dose
	D3	Alum dose
	D4	DAF loading rate/Flocculator tank detention time
	D5	Flocculator tank velocity gradient
Particle volume distribution	D6	Ozone dose
	D7	Ozone dose
	D8	Alum dose
	D9	DAF loading rate/Flocculator tank detention time
	D10	Flocculator tank velocity gradient

Figures D1 to D2 and D5 to D6 show PSD diagrams for the effects of ozone. The number concentration diagram indicates that the greatest number of particles in the system has a mean diameter of 3 μm (2 to 4 μm range). This size range is the smallest that the potable water sensor could analyze. As the mean particle diameter increases, the number of particles in that size range decreases. This general pattern is the same no matter which coagulant is used or which sampling point is analyzed. When the coagulant is added, particle number concentrations increase by over two times. The DAF unit then significantly reduces the number of particles in the water, its effectiveness is dependant on a number of parameters. The filters further reduce the number of particles in the system. This general pattern is also maintained regardless of the treatment parameters.

Results for both number concentration PSD's showing the effects of ozone, indicate that the number of particles added to the system after the addition of the coagulant is less when ozone is used. In effect, this is indicating that the DAF and filters will have to do less work when ozone is used. However, as indicated in Section 5.1.3, particle reduction in the DAF unit is sometimes less with ozone, depending on the dose and raw water conditions. Figure D1 indicates that ozone is deleterious for particle removal in the DAF unit. However, Figure D2 shows that particle reduction in the DAF tank is virtually the same, or slightly reduced with ozone. In fact, in terms of absolute number of particles, there is less in the ozonated system than in the non-ozonated one. The raw water turbidity and UV-absorbance were greater when runs to create Figure D2 were performed, again indicating a critical concentration of NOM for ozone to work in these applications. There is little evidence of a shift in the particle size distribution to larger sizes as a result of ozone addition.

The volume concentration diagrams show similar results as the number concentration diagrams. Volume concentration diagrams emphasize larger particles. Because of their size and their number, particles with a mean diameter of 12 μm occupy the largest space per unit volume of water. Volume concentration data has been normalized with respect to the particle size. There does not appear to be any particle shift from lower sizes to larger diameters following coagulation and flocculation with ozone in the system.

There is an obvious difference in particle behavior when there is a change in coagulant dose from 10.0 mg/L to 4.0 mg/L (refer to Figures D3 and D8). With this raw water quality (turbidity = 0.20 NTU), there is an obvious advantage for particle removal, in terms of number and volume, when an alum dose of 10.0 mg/L is used and compared to a dose of 4.0 mg/L. Similar to PSD diagrams with ozone as the independent variable, there appears to be no particle size shift with different alum doses.

It appears that higher flow rates create a larger number and volume of particles after coagulation. The increased turbulence and shear forces resulting from higher flows likely breaks up the coagulated particles into smaller pieces. Because particles are counted in a particular size range (i.e. 2 to 4 μm), a particle can break up and still be counted in the same size range, thereby increasing their numbers in that range. Figures D4 and D9 indicate that there is a smaller overall number and volume of particles with lower flows in the DAF effluent. Fewer particles in the DAF effluent will result in less particle loading to the filters.

There is very little difference in the number concentration or volume concentration of particles in any size range, when the velocity gradient is changed from $30s^{-1}$ to $100s^{-1}$ (refer to Figures D5 and D10). There are slightly fewer particles in the DAF effluent with the lower velocity gradient, however, this difference is very small and may simply be due to randomness in the system. Filter effluent quality is nearly the same regardless of the velocity gradient.

5.1.5 Colour and UV_{254} Removal

Results presented in Section 5.1.3 show that organic matter as measured by UV-absorbance is removed by adsorption onto coagulant precipitates before the DAF unit. However, this is not the case with colour-causing organic compounds. The colour that is removed from the water before the filters is nearly all done in the DAF unit. This indicates that these colour-causing compounds, commonly humus, plankton, weeds, iron and manganese are not the same compounds that absorb UV-light at a wavelength of 254 nm. This means that UV-absorbance and colour are surrogate measures of different kinds of organic matter.

Because colour is mainly removed in the DAF tank by the same mechanisms that remove particles, the higher the turbidity reduction in the DAF tank, the higher the colour removal. Figure D11 in Appendix D shows percent removal of turbidity in the DAF tank versus percent removal of colour in the DAF tank. Data points on the graph are for all runs performed with alum as the coagulant and where colour and turbidity measurements were taken. The figure shows an obvious positive correlation between percent removal of turbidity and percent removal of colour. This analysis was not intended to compare ozonated and non-ozonated samples.

5.1.6 Summary Information

This section provides summary information for the effects of four independent variables: ozone dose, alum dose, DAF flow and velocity gradient on treated water quality. This section collates findings already presented in Section 5.1.3. Figures D12 to D16 in Appendix D plot percent reduction y-axis versus a number of water quality measures such as turbidity, particle counts, colour and UV-absorbance. All percent reductions are for the DAF tank, except for UV_{254}, which measures the reduction from the raw water to the sampling point immediately after coagulant addition.

The effect of ozone on the flocculation of particles and DAF performance were two major objectives set at the beginning of this study. Figures D12 and D13 summarize the effects of ozone on the removal of particles in the DAF unit for two different raw water qualities. Alum dose and ozone doses are indicated on the graphs. All other parameters were held constant. The only difference in testing conditions for the runs represented on Figures D12 and D13 is the quality of the raw water. Runs shown on Figure D12 were performed in late August were the turbidity was very good, around

0.18 NTU. Runs performed to create Figure D13 were performed when the raw water turbidity was 0.40 NTU, and the UV-absorbance was 0.075 cm^{-1}. No colour measurements were collected for these runs. No UV measurements were taken at the time when the runs shown on Figure D12 were performed. However, based on historical data, a reduction in turbidity is usually accompanied by a reduction in UV-absorbing organic matter. Figure D12 shows that as the ozone dose is increased from 0.00 mg/L to 0.50 mg/L, the number of particles removed in the DAF decreases substantially. Similarly, turbidity removal is reduced with the increase in ozone dose. Particles greater than 2 μm were reduced by 80 percent in the DAF unit when no ozone was applied. With the addition of 0.50 mg/L of ozone, particle reduction in the DAF unit was 9 percent. Conversely, Figure D13 shows a positive response to the addition of ozone to the system. For these runs, turbidity and particle reduction increase by approximately 5 percent. Although this increase is small, and may in fact be attributed to randomness, these results are very different than what Figure D12 indicated. It is clear that raw water quality is extremely important since that was the only factor that was different for these two sets of runs. Figure D13 also indicates that UV_{254} removal increased by over 10 percent as a result of pre-ozonation. UV_{254} was reduced by between 80 and 90 percent after coagulant addition. Although it is possible that increased particle reduction is attributable to randomness, this explanation is unlikely to be applicable to UV-absorbance reduction. Not only was UV_{254} reduced by an additional 10 percent with ozone as opposed to a 5 percent increase in particle reduction, but also more runs supported this finding, than with particle removal improvement. In addition, results indicate that even if particles are negatively affected by ozone addition, UV_{254} removal remains the same or still improves. This finding is consistent with all coagulants tested.

It is important to have the coagulant dose (and coagulating pH) optimized for flocculation to occur. Figure D14 in Appendix D shows that only a small change in alum dose changes particle and turbidity removal in the DAF tank significantly. For the illustration presented in Figure D14, the alum dose was only decreased from 10.0 mg/L to 6.0 mg/L, but turbidity removal in the DAF unit decreased from 67 to 12 percent. The raw water turbidity was approximately 0.21 NTU at the time of these runs. This behavior is similar regardless of the raw water turbidity. The removal of organic matter measured by UV_{254}, prior to the DAF unit, is not as sensitive to changes in coagulant dose.

The flow of water through the DAF/flocculation unit is controlled by a rotameter between the ozone pumps on the first floor and the in-line static mixers on the mezzanine level. Therefore, a change in DAF loading rate (flow through the DAF tank per unit of surface area) will also result in a change in flocculation time and DAF saturator recycle ratio. Which factor dominates may be difficult to distinguish. Figure D15 in Appendix D shows that an increase in flow results in a negative response for particle and turbidity removal in the DAF tank. It is believed that this is not due to the change in flocculation time or recycle ratio. The recycle ration only changed from 11 to 12 percent and the flocculation time only decreased by 2 minutes as a result of the higher flows. The change is more likely due to the higher DAF loading rates and the resulting flow pattern disruption in the flotation cell. The plume of air bubbles in the flotation tank seems to disperse more when the flow increases, likely resulting in the poorer performance. Better tank design and baffle placement may help this problem.

Figure D16 in Appendix D shows that there is very little difference in DAF performance when the velocity gradient of the flocculators is changed. A change in velocity gradient from 30 s^{-1} to 100 s^{-1} resulted in very little change in particle or turbidity removal. This upper limit was not enough to break apart floc particles and the lower limit was high enough to allow enough contact between destabilized particles to create a good, strong stable floc. Velocity gradients outside this range had a much larger effect on DAF performance.

5.2 Polyaluminum Chloride

5.2.1 Experimental Conditions

PACl testing was carried out in two phases. The first set of experiments took place between September 27 and October 19, when the turbidity was low (0.32 NTU) and the temperatures relatively high (13°C). The second set of runs occurred between November 11 and December 1, when the turbidity and organic matter content were much higher and the temperatures much lower. Polyaluminum chloride (or aluminum hydroxychloride), like alum, is an aluminum-based coagulant. However, it has other properties that make it suitable for treatment of water with low alkalinity. As discussed in Section 2.3, PACl consumes less alkalinity than alum and ferric chloride. It has also been found that it may require a smaller dose than either alum or ferric chloride for equal removals of turbidity, (Schneider, *et al.*, 1991). For these reasons, it was included as part of the testing program for the Seymour pilot plant study.

There are a number of different types of PACl available. It is not a pure substance like alum or ferric chloride, but a complex mixture of a number of molecular compounds, (Bunker Jr., *et al.*, 1995). Some PACl's will also have substances such as calcium, silicon and sulfate in them. High basicity and low basicity PACl can also be acquired. The PACl that was used in this study was manufactured by ClearPAC and distributed by PrarieChem Inc. The product was shipped in 25 kg pails as a clear to slightly yellowish, odorless liquid. PACl can have a specific gravity between 1.22 and 2.8, depending chemical make-up. The PACl used in this study had a specific gravity of 1.24. The pH of the solution was between 2.2 to 2.8. ClearPAC has 34% solids by weight with 9.7 to 10.3 percent Al_2O_3 by weight. It also has 50 to 58 percent basicity. PACl is also very soluble in water, which means that continuous mixing is not required. The concentrations used in this study are based on total weight of solids and not as concentration of aluminum ions (Al^{3+}). Coagulant mixing recipes are located in the plant operation manual in Appendix A.

Figures 3.2.1 through 3.2.6 in Section 3.2 show raw water quality measurements taken during the pilot plant study period, for a number of parameters. Shown are turbidity, temperature, pH, UV-absorbance, colour and particle counts for the period between July 26 and December 14. Turbidity and particles remained relatively constant during Phase I PACl testing between September 27 and October 19. Some rain fell in the middle of October, and as a result, the turbidity rose slightly from a value of 0.33 NTU on September 27 to a value of 0.40 on October 19. There was also a corresponding increase in particle counts. The amount of organic matter also increased, as indicated by an increase in colour and UV-absorbance measurements. Colour increased from 14 to 27 ACU and UV_{254} values increased from 0.052 to 0.084 cm^{-1}. Because of cooler air temperatures as summer ended, water temperatures decreased from 13.2 to 10.6 °C.

Phase II PACl testing started at the tail end of the turbidity event that occurred at the beginning of November. Alum testing was performed during the peak of the event, however turbidity on November 19 at the beginning of PACl testing was 1.88 NTU. By December 1, it had rapidly and steadily decreased to 0.63 NTU. Particle counts followed a similar trend. The amount of organic matter during this time, as expressed by UV-absorbance, decreased slightly from 0.108 to 0.087 cm^{-1}. Colour and temperature stayed almost constant at 30 ACU and 6.2 °C, respectively. Table 5.2.1 below, summarizes raw water conditions for phase I and phase II PACl testing. The range of values indicated are for the beginning and end of each testing phase, respectfully.

Table 5.2.1 Raw water characteristics during PACl testing

	Period	
	September 27 to October 19	November 19 to December 1
Turbidity (NTU)	0.33 to 0.40	1.88 to 0.63
Particles, >2 µm (#/mL)	465 to 771	4262 to 1535
Particles, >4 µm (#/mL)	219 to 393	2084 to 717
Particles, >8 µm (#/mL)	80 to 128	551 to 194
Particles, >16 µm (#/mL)	2 to 1	1 to 2
Particles, >32 µm (#/mL)	0	0
Particles, >50 µm (#/mL)	0	0
Colour (ACU)	14 to 26	34 to 29
UV_{254} (cm^{-1})	0.052 to 0.084	0.108 to 0.087
Temperature (°C)	13.2 to 10.6	7.1 to 6.4

Most of the systems in the pilot plant ran well for phase 1 PACl testing. However, between October 15 and October 18, filter number four was unable to perform a backwash. The actuator was cleaned on October 18, which alleviated the problem. No major operational problems occurred during the second testing session. The ozone residual monitor that started to malfunction at the beginning of September had not been fixed. It remained down until the end of the pilot plant study.

5.2.2 Experimental Design Description

Like alum testing, factorial design experiments were run with PACl when raw water conditions allowed. As noted in the Section 5.2.1, raw water conditions for the testing period between September 27 and October 19 were relatively constant, with turbidity ranging from 0.33 to 0.40 NTU. Colour and UV-absorbance increased slightly during this period.

Table C2 in Appendix C summarizes run information for each run performed for the pilot plant study, including PACl. The table includes run number, start time, ozonation conditions, coagulation conditions, flocculation conditions, DAF conditions and filtration conditions. Each one of these runs have been grouped into smaller sub-sections, and are described in more detail as follows.

Test runs 0927ar to 1001aw, 1004ay, 1004az, 1015be

Nine runs between September 27 and October 15 were performed as part of a 2^3 factorial design. Run 1015be is a centerpoint replicate, meaning its levels were set halfway between the positive and negative levels of the other runs. Alum dose, ozone dose and DAF flow (loading rate) were the factors used for the experimental design described below in Table 5.2.2.

Table 5.2.2 Factorial design I for PACl

	Level		
Factor	-	(0)	+
Coagulant dose (mg/L), A	4	7	10
Ozone dose (mg/L), B	0	0.25	0.5
Flow (LPM), C	70	85	100

Runs corresponding to the above factorial design are located below in Table 5.2.3

Table 5.2.3 Run information for PACl factorial design I

	Factor		
	A	B	C
0927ar	+	-	+
0928as	+	+	+
0928at	-	+	+
0929au	-	-	+
1001av	+	-	-
1001aw	-	-	-
1004ay	+	+	-
1004az	-	+	-
1015be		Center Points	

The levels for the PACl dose were loosely based on doses used for alum testing. Ozone dose levels were determined from past experience at the pilot plant and the flow was governed by the capacity of the ozone columns and pumps to deliver water to the mezzanine level. Flocculation conditions remained constant this set of runs. The velocity gradient remained at 51 s^{-1}. The DAF saturator pressure fluctuated slightly between 400 and 440 kPa, with 2 higher readings at 540 kPa on September 29 and October 1. It was not thought that these high values would have a great effect on the results. DAF recycle ratio varied between 9 and 12 % as a result of the different flows entering the DAF/flocculation tank. Filtration operating conditions remained constant at the values set earlier in the study. Soda ash doses remained relatively constant, resulting in a final effluent pH of between 6.3 and 6.5.

Test runs 1005ba, 1006bd, 1016bg, 1018bj

The above four runs were performed at an elevated PACl dose of 15 mg/L. Runs 1005ba and 1006bd were run at a DAF flow rate of 70 LPM, while runs 1016bd and 1018bj were run at a flow rate of 90 LPM. Ozone dose was also varied. Flocculation conditions remained consistent with a velcocity gradients of 51s^{-1}. DAF saturator pressure fluctuated slightly between 400 and 420 kPa. Table 5.2.4 below, summarizes experimental conditions for these runs.

Table 5.2.4 Experimental Conditions, runs 1005ba, 1006bd, 1016bg and 1018bj

	Run			
	1005ba	1006bd	1016bg	1018bj
PACL dose (mg/L)	15.0	15.0	15.0	15.0
Ozone dose (mg/L)	0.28	0.56	0.00	0.27
Flow (LPM)	70	70	90	90
Flocculation stages (#)	3	3	3	3
Flocculator velocity gradient (s^{-1})	51	51	51	51
DAF recycle ratio (%)	12	11	9	10
DAF saturator pressure (kPa)	400	420	420	420

Test runs 1005bb, 1006bc

Runs 1005bb and 1006bc were performed to test the effects of soda ash on the effectiveness of PACl as a coagulant. No soda ash was used for run 1005bb, while approximately 10.0 mg/L was used for run 1006bc. As noted in Section 2.2, only one hydroxide ion is used for every two aluminum ions when PACl is added to water, therefore less soda ash is needed with PACl than for alum or ferric chloride to keep the pH within optimum levels for precipitates to form. The final pH for run 1005bb was 6.2 and 6.9 for run 1006bc. Their effects on DAF removal efficiencies will be discussed in the Section 5.2.3.

Test runs 1002ax, 1015bf, 1016bh, 1018bi, 1019bk

Run 1002ax was performed at the same time as the first factorial design for the phase I PACl testing. The run was carried out overnight and used an ozone dose of 0.32 mg/L and a coagulant dose of 10.0 mg/L. The remaining runs in this section were miscellaneous runs that were either abandoned, or produced no floc in the DAF unit because of mechanical problems, or chemical dosing problems.

Test runs 1119cv to 1124da

The purpose for performing runs 1119cv through 1124da was to reestablish optimum PACl doses for treating water with higher turbidities. This set of runs was the first to be performed for the phase II PACl testing. These 6 runs were performed using the one-variable-at-a-time method of experimentation, with coagulant dose as the only independent variable. All other parameters were held constant. PACl doses tested ranged from 10.0 mg/L to 50.0 mg/L. The turbidity of the raw water for these runs was between 1.88 NTU on November 19 to 1.25 NTU for run 1124da, performed on November 24. These values represent the tail end of the mid-November high turbidity event that elevated turbidity levels from about 0.20 NTU to 2.29 NTU over two weeks at the beginning of November. The temperature of the raw water was approximately 7°C during these runs.

Test runs 1125db to 1130dm

Runs 1125db to 1130dm, with the exception of runs 1125dd, 1125de, 1126df and 1126di, were performed for a factorial design with ozone dose, DAF flow and flocculator velocity gradient as the parameters. Alum dose was held constant at 30 mg/L. Table 5.2.5 below shows the factorial design.

Table 5.2.5 Factorial design, runs 1125db to 1130dm

	Level	
Factor	-	+
Ozone dose (mg/L), A	0.25	0.75
Flow (LPM), B	60	90
G (s-1), C	30	70

Runs corresponding to the above factorial design are located below Table 5.2.6.

Table 5.2.6 Run information for PACl factorial design II

	Factor		
	A	B	C
1125db	-	-	-
1125dc	+	-	-
1126dg	-	-	+
1126dh	+	-	+
1129dj	-	+	-
1129dk	-	+	+
1129dl	+	+	-
1130dm	+	+	+

Although the coagulant dose remained constant, it should be noted that the turbidity of the raw water dropped by approximately 0.35 NTU from 1.07 NTU on November 25 to 0.71 NTU on November 30. This decrease in the raw water characteristics may skew the results of the factorial design, since a drop of 0.35 NTU is enough to change the optimum coagulant dose by several ppm.

Runs 1125dd and 1126df were performed with a coagulant dose of 40 mg/L. While this dose produced a very good floc in run 1124cz when the turbidity was 1.25 NTU (over 80% reduction in turbidity), the turbidity reduction for runs 1125dd and 1126df were negligible or negative. The raw water turbidity was approximately 0.95 NTU. These two runs demonstrated the decrease in coagulant demand with decreasing suspended particles in the raw water. Runs 1125de and 1126di were repeats of runs 1124cy and 1125db, respectively.

Test runs 1130dn to 1201dr

The remaining 5 runs for PACl testing were performed when the turbidity was decreasing rapidly. The turbidity at the end of the second phase of PACl testing was 0.63 NTU. The purpose of these runs was to investigate lower coagulant doses for raw water with lower turbidity than earlier in phase II. Coagulant doses of 10.0 mg/L to 30.0 mg/L were tested with ozone doses ranging from 0.00 to 0.75 mg/L. Flocculation and DAF operating conditions remained constant. Testing conditions are summarized below in Table 5.2.7.

Table 5.2.7 Testing conditions for runs 1130dn, 1130do, 1201dp, 1201dq, 1201dr

Parameter	1130dn	1130do	1201dp	1201dq	1201dr
PACl dose (mg/L)	30.0	20.0	20.0	20.0	20.0
Ozone dose (mg/L)	0.26	0.00	0.28	0.00	0.75
Raw water turbidity (NTU)	0.71	0.71	0.63	0.63	0.63

5.2.3 Presentation of Results

A summary of results for all runs performed for the Seymour pilot plant study is located in Table C3 in Appendix C. Detailed discussions on the results of PACl testing are located in the following sections. Runs are grouped in the same manner as in Section 5.2.2.

Test runs 0927ar to 1001aw, 1004ay, 1004az, 1015be

Table 5.2.8 on the following page shows DAF removal efficiencies for turbidity, particle counts, colour and UV_{254}. UV_{254} reduction is also shown for the sampling point just after the in-line mixtures.

Table 5.2.8 Results for PACl factorial design (I)

Treatment Combination	1 (1001aw)	A (1001av)	B (1004az)	AB (1004ay)	C (0929au)	AC (0927ar)	BC (0928at)	ABC (0928as)	Center Points (1015be)
DAF turbidity reduction (%)	-2	58	2	67	-9	27	-1	12	-8
DAF particle reduction, >2 µm (%)	3	60	17	66	-9	57	-11	13	-9
DAF particle reduction, >4 µm (%)	4	65	17	64	-4	65	-10	16	-4
DAF particle reduction, >8 µm (%)	3	65	17	59	-1	68	-12	24	3
DAF colour removal (%)	10	60	13	75	-	-	-	-	0
UV_{254} removal after coagulation (%)	0	66	40	89	0	46	27	64	23
DAF UV_{254} removal (cm^{-1})	0.000	0.006	0.004	0.001	0.000	-	0.003	0.003	-0.003
Post-DAF UV_{254} (cm^{-1})	0.058	0.013	0.033	0.006	0.056	0.042	0.035	0.016	0.057

Experimental conditions for the runs for this factorial design were detailed in Section 5.2.2. Factorial designs are designed for determining which factors or parameters are significant. That is, those factors that causes in the greatest effect on the response variables. For this factorial design, the response variables are turbidity, particle counts, colour reduction in the DAF unit, as well as UV_{254} reduction immediately following coagulant addition. Each step for analyzing factorial designs will be presented and briefly explained below.

The first step for determining the significant effects is to create a table of contrast coefficients (table of signs) as shown below in Table 5.2.9. Only one response variable is shown in Table 5.2.9. Similar tables could be made for each of the response variables being studied. It is important to determine the effects of the factors on different response variables as coagulant dose, for example, may have a different effect on turbidity than it does on colour.

Table 5.2.9 Table of signs for PACl factorial design (I)

		Main Effects			Interactions				
Run #	Mean	A (Coagulant Dose)	B (Ozone Dose)	C (Flow)	AB	AC	BC	ABC	Turbidity (NTU)
1 (1001aw)	1	-1	-1	-1	1	1	1	-1	-2
2 (1001av)	1	1	-1	-1	-1	-1	1	1	58
3 (1004az)	1	-1	1	-1	-1	1	-1	1	2
4 (1004ay)	1	1	1	-1	1	-1	-1	-1	67
5 (0929au)	1	-1	-1	1	1	-1	-1	1	-9
6 (0927ar)	1	1	-1	1	-1	1	-1	-1	27
7 (0928at)	1	-1	1	1	-1	-1	1	-1	-1
8 (0928as)	1	1	1	1	1	1	1	1	12
Divisor	8	4	4	4	4	4	4	4	

High and low levels are coded with a positive sign and a negative sign, respectively. An example calculation for determining the A main effect is shown below (Equation 5.2.1). The divisor is the number of positive signs in each column (i.e. 8 for the first column, 4 for the second column,.....). Calculations for other effects are done in a similar way.

Equation 5.2.1 Effects

$$Effect(A) = \frac{(-1)(-2.2)+(1)(57.5)+(-1)(2.1)+(1)(66.6)+(-1)(-9.1)+(1)(26.6)+(-1)(-0.8)+(1)(11.5}{4}$$

$$= 43.1$$

A summary of the main effects and interactions for selected response variables is shown in Table 5.2.10, below. For effects to be calculated, the data set for the response variable must be complete. Therefore effects for colour could not be calculated for this design.

Table 5.2.10 Calculated main effects and interactions for PACl factorial design (I)

	DAF Percent Reduction				
Main Effects	Turbidity	Particles, >2	Particles, >4	Particles, >8	UV_{254} (post-coag)
PACl dose, A	43.1	49.2	50.5	52.1	49.3
Ozone dose, B	1.7	-6.7	-10.3	-11.9	26.8
DAF Flow, C	-24.0	-24.0	-20.8	-15.9	-14.6
Interactions	Turbidity	Particles, >2	Particles, >4	Particles, >8	UV_{254} (post-coag)
AB	-4.7	-12.5	-14.5	-13.3	-6.8
AC	-19.1	-3.6	-3.3	0.5	-7.9
BC	-5.1	-16.4	-16.7	-15.5	-4.7
ABC	-7.1	-8.2	-7.2	-3.1	2.0

An effect is significant if it is much greater than the rest of the effects for a particular response variable, (Box *et al.,* 1978). For the above factorial design, the average response of turbidity to a change in factor A, or in this case coagulant dose, is 43.1 units. That is to say, the average response of changing the PACl dose level from 4.0 mg/L to 10.0 mg/L, as stated in the factorial design, is to increase the turbidity removal in the DAF unit by 43.1 percent. The response for each main effect or interaction can be interpreted in the same manner. From the above table, it is fairly evident that factor A, or coagulant dose, has the greatest effect on all of the response variables. The effect of ozone on the response variables is very small compared to coagulant dose. Small effects are most often attributed to randomness in the system. However, it should be noted that ozone had a negative effect on turbidity and particle removal, but a positive effect on the removal of UV_{254} following coagulation. This finding is similar to results from alum testing. In this design, the ozone dose was changed from 0.0 mg/L to 0.50 mg/L. Though the effects of ozone on the response variables at these low doses were not significant, previous results have shown that more elevated ozone doses (greater than 1.0 mg/L) destroy the floc.

The effect of flow on the effectiveness of the DAF unit to remove suspended particles is less significant than coagulant dose, but more significant than ozone dose. Increasing the flow from 70 to 100 LPM decreases the removal efficiency of all the response variables by approximately 25 percent each. Increasing the flow rate into the integrated DAF unit not only increases the DAF loading rate, but it decreases the flocculation time the recycle ratio as well. Therefore it is difficult to see from the data, which factor is responsible for the change in DAF efficiency. Flocculation times remained reasonable despite the change, and the recycle ratio only changed from 12 to 9 percent. It is therefore likely that the decreased removal efficiency in the DAF was due to a disruption in the flow patterns in the flotation cell itself. This means that the air bubble plume spread out, not allowing proper flotation of the bubbles to the surface of the DAF cell. It is likely that some particles did not properly attach to the air bubbles and settled to the bottom of the flotation cell.

Another way for determining significant effects is to draw a normal probability plot (Box, *et al.*, 1978). When estimated effects are plotted against a normal score, the random effects, or those due to noise in the system, fall on a straight line. Normal probability plots for turbidity, particle greater than 2 μm and UV_{254} removal by absorption are located in Appendix E, and labeled Figures E1, E2, and E3. These plots confirm the previous statements that coagulant dose is the most significant effects with respect to all of the response variables. The plots also indicate that flow is important as well as ozone dose for the removal of organic matter following coagulation.

Similar to the results obtained from alum testing, most of the organic matter as measured by UV_{254} is removed immediately after coagulant addition. In addition, when the turbidity removal efficiency in the DAF unit is high, so too is the UV_{254} removal prior to the DAF unit. However, like results with alum, UV_{254} can still be effectively removed even if turbidity removal is poor if low ozone doses are used.

Test runs 1005ba, 1006bd, 1016bg, 1018bj

Results for the above four runs, which used a PACl dose of 15.0 mg/L, and a variety of flows and ozone doses, are summarized in Table 5.2.11 below.

Table 5.2.11 Results for runs 1005ba, 1006bd, 1016bg, 1018bj

Response Variables	1005ba	1006bd	1016bg	1018bj
DAF turbidity reduction (%)	71	77	71	67
DAF particle reduction, >2 µm (%)	81	85	76	63
DAF particle reduction, >4 µm (%)	78	87	78	67
DAF particle reduction, >8 µm (%)	80	86	83	66
DAF colour removal (%)	60	60	65	44
UV_{254} removal after coagulation (%)	88	93	88	82

It appears that particle reduction is lower in runs 1016bg and 1018bj than for 1005ba and 1006bd. The former two runs had a flow rate of 90 LPM versus a flow rate of 70 LPM for runs 1005ba and 1006bd. Colour reduction was not as good as has been previously seen. It was particularly low for run 1018bj. This run also had the lowest turbidity and particle removal rates. It appears that the effect of ozone at the doses chosen for these runs (between 0.0 mg/L and 0.50 mg/L) did not have a significant effect on the data. The only notable effect may be a slightly higher removal of UV_{254} after coagulation. However, higher removal rates of UV_{254} after coagulation with ozone is consistent with the results from the first PACl factorial design.

Test runs 1005bb, 1006bc

Two runs were performed to test the effect of soda ash on the coagulation and flocculation of PACl. Results for these two tests are shown below in Table 5.2.12. Run 1005bb used 0.0 mg/L of soda ash, while run 1006bc used 5.0 mg/L.

Table 5.2.12 Results for soda ash test with PACl

Treatment	(1006bc)	(1005bb)
Soda ash dose (mg/L)	5.0	0.0
DAF turbidity reduction (%)	6	68
DAF particle reduction, >2 µm (%)	-7	86
DAF particle reduction, >4 µm (%)	-8	87
DAF particle reduction, >8 µm (%)	-15	88
DAF colour removal (%)	-13	60
UV_{254} removal after coagulation (%)	28	85
Post-DAF UV_{254} (cm^{-1})	0.025	0.008
pH	6.9	6.2

It is clear from the above results that soda ash is not required when PACl is used as the coagulant. The pH remains above 6.0 with no soda ash addition, and particle removal in the DAF unit is good. Removal of organic matter is also high.

Test runs 1002ax, 1015bf, 1016bh, 1018bi, 1019bk

Only run 1002ax, of the remaining five runs performed in phase I of PACl testing resulted in DAF removal rates greater than 50 % for particles, turbidity and colour. The other run did not work because of improper coagulant doses. Run 1002ax was run overnight. Filter results for this run will be presented in Section 5.2.7.

Test runs 1119cv to 1124da

Runs 1119cv to 1124da were carried out at the tail end of the high turbidity event that occurred in the middle of November. The purpose of these runs was to reestablish proper PACl doses at these higher turbidities. Results are located below in Table 5.2.13.

Table 5.2.13 Results for PACl dose establishment, Phase I

	Run					
	1119cv	1123cw	1124cx	1124cy	1124cz	1124da
PACL dose (mg/L)	10.0	12.0	20.0	30.0	40.0	50.0
DAF turbidity reduction (%)	-	-	-2	83	80	-196
DAF particle reduction, >2 µm (%)	-	-	-19	78	87	-57
DAF particle reduction, >4 µm (%)	-	-	-24	77	88	-129
DAF particle reduction, >8 µm (%)	-	-	-33	73	87	-332
DAF colour removal (%)	-	-	-	64	67	21
UV_{254} removal after coagulation (%)	-	-	47	92	92	81
Post-DAF UV_{254} (cm^{-1})	-	-	0.038	0.009	0.005	0.010

No data were recorded for runs 1119cv and 1123cw because no floc was formed. With respect to turbidity and particle removal, a PACl dose of 40.0 mg/L appears to be optimum for this water quality. The raw water turbidity on November 24 was 1.25 NTU. This is compared to an optimum coagulant dose of 10.0 to 15.0 mg/L when the raw water turbidity was approximately 0.375 at the beginning of October. This demonstrates that coagulant demand increases greatly with relatively small changes in raw water turbidity. Organic matter was removed well with a PACl dose of 30.0 and 40.0 mg/L. It is interesting to note that when a dose of 50.0 mg/L was used, turbidity and particles were not removed by the DAF unit, however, organic matter removal, particularly UV-absorbance, was comparable to previous runs. This would indicate that there is a minimum coagulant dose for UV-absorbance removal by absorption, but not a maximum. The temperature of the water for phase II of PACl testing remained near 6.0°C, which indicates that PACl works well under cold water conditions.

Test runs 1125db to 1130dm

With the exception of runs 1125dd, 1125de, 1126df and 1126di, the runs 1125db to 1130dm were used as part of a factorial design with ozone dose, flocculator velocity gradient and DAF flow as parameters. It was not thought that these factors would have interaction effects, however, it was believed that these parameters were the most important to be tested at that time. The PACl dose was kept at 30.0 mg/L. The turbidity dropped from 1.07 NTU on November 25 to 0.712 on November 30, therefore results from this design must be interpreted with caution. Results for the runs associated with the factorial design are shown below in Table 5.2.14

Table 5.2.14 Results for PACl factorial design (II)

Treatment Combination	1 (1125db)	A (1125dc)	B (1129dj)	AB (1129dl)	C (1126dg)	AC (1126dh)	BC (1129dk)	ABC (1130dm)
DAF turbidity reduction (%)	83	78	66	69	81	82	69	66
DAF particle reduction, >2 µm (%)	[illegible]	79	74	69	80	83	60	66
DAF particle reduction, >4 µm (%)	89	79	79	74	78	83	68	70
DAF particle reduction, >8 µm (%)	89	72	84	78	70	79	71	71
DAF colour removal (%)	53	9	37	4	-	36	40	16
UV_{254} removal after coagulation (%)	90	93	89	94	91	90	94	89
Post-DAF UV_{254} (cm^{-1})	0.008	0.009	0.005	0.003	0.006	0.009	0.006	0.010

A sample design matrix for this problem, with turbidity as the response variable, is shown below in Table 5.2.15.

Table 5.2.15 Design matrix for PACl factorial design (II)

	Main Effects				Interactions				
Run #	Mean	A (Ozone Dose)	B (Flow)	C (G)	AB	AC	BC	ABC	Turbidity (NTU)
1 (1125db)	1	-1	-1	-1	1	1	1	-1	83
2 (1125dc)	1	1	-1	-1	-1	-1	1	1	78
3 (1129dj)	1	-1	1	-1	-1	1	-1	1	66
4 (1129dl)	1	1	1	-1	1	-1	-1	-1	69
5 (1126dg)	1	-1	-1	1	1	-1	-1	1	81
6 (1126dh)	1	1	-1	1	-1	1	-1	-1	82
7 (1129dk)	1	-1	1	1	-1	-1	1	-1	69
8 (1130dm)	1	1	1	1	1	1	1	1	65
Divisor	8	4	4	4	4	4	4	4	

The main effects and interactions for selected response variables are located below in Table 5.2.16.

Table 5.2.16 Main effects and interactions for PACl factorial design (II)

	DAF Percent Reduction					
Main Effects	Turbidity	Particles, >2	Particles, >4	Particles, >8	Colour	UV_{254} (post-coag)
Ozone dose, A	-1.3	-1.4	-2.1	-3.5	-16.2	0.6
DAF flow, B	-13.6	-15.3	-9.5	-1.4	-0.4	1.0
Flocculator G, C	0.4	-5.6	-5.4	-7.9	-2.8	-0.2
Interactions	Turbidity	Particles, >2	Particles, >4	Particles, >8	Colour	UV_{254} (post-coag)
AB	1.1	1.6	0.8	0.3	-12.2	-0.4
AC	-0.5	5.7	5.7	8.1	22.4	-3.7
BC	-0.8	-3.4	-2.3	-1.9	10.2	0.5
ABC	-3.1	-0.4	-2.1	-4.9	-17.9	-1.6

From Table 5.2.3.9, it is clear that DAF flow has the most significant effect on turbidity and particle reduction in the DAF unit. However, an increase in flow from 60 LPM to 90 LPM only resulted in an average decrease in the removal efficiency of the DAF with respect to turbidity of approximately 13 percent. Compared to results of the first factorial design for PACl, this is not very large. In that design, the main effect of coagulant dose on turbidity was 43 percent and the main effect of flow on turbidity was –24 percent. None of the factors have large effects on the removal of organic matter as measured by UV-absorbance. Higher ozone doses had the effect of reducing colour removal in the DAF unit by an average of 16 percent. All response variables did not react greatly to changes in flocculator velocity gradient in the ranges tested. As expected, none of the two-factor interactions have an effect on any of the response variables.

Runs to test the higher DAF flow of 90 LPM were all performed on November 29 and 30 when the turbidity was lower than for tests performed on November 25 and 26. Based on the fact that increased flow had a similar effect on DAF performance in the first factorial design, it is not believed that the decrease in raw water turbidity is responsible for the decreased DAF efficiency in this factorial design. As stated earlier, the higher flows likely disrupt the flow patterns of the air bubble plume.

Normal probability plots for turbidity and particles greater than 2 μm are labeled Figures E4 and E5 and are located in Appendix E. These plots indicate that flow is in fact the most significant factor for turbidity and particle removal. However, none of the parameters had a significant effect on colour and UV-absorbance. Any variations in colour or UV_{254} measurements were likely due to noise.

Turbidity removal in the DAF unit when the flow was 60 LPM ranged from 78 to 83 percent. In the first factorial design with PACl, where the raw water turbidity was much lower, optimum turbidity removal ranged from 58 to 67 percent. When the PACl dose was 15.0 mg/L for runs 1005ba, 1006bd, 1016bg, and 1018bj, and the raw water turbidity was slightly higher than in the first factorial design, turbidity removals in the DAF unit were 67 to 77 percent. These results indicate that the DAF unit is much more efficient at removing suspended particles when the raw water turbidity is around 1.0 NTU, rather than 0.20 to 0.40 NTU. The same can be said for the removal of organic matter. Removal efficiencies of UV-absorbance immediately following coagulant addition were much better for the second phase PACl runs than they were for the first phase runs where the raw water quality was better.

Test runs 1130dn to 1201dr

Results for runs 1130dn to 1201dr are listed below in Table 5.2.17.

Table 5.2.17 Results for runs 1130dn, 1130do, 1201dp, 1201dq, 1201dr

Response Variables	1130dn	1130do	1201dp	1201dq	1201dr
DAF turbidity reduction (%)	80	70	54	-	50
DAF particle reduction, >2 µm (%)	80	68	80	-	52
DAF particle reduction, >4 µm (%)	80	72	80	-	57
DAF particle reduction, >8 µm (%)	77	70	77	-	59
DAF colour removal (%)	44	34	4	-	10
UV_{254} removal after coagulation (%)	89	90	37	-	81

Run 1201dq was abandoned and therefore no measurements were taken. The raw water turbidity during these runs ranged from 0.71 to 0.63 NTU. The coagulant dose for these runs was 20.0 mg/L, with the exception of run 1130dn, where the coagulant dose was 30.0 mg/L. Runs 1201dp and 1201dr are the same except for an increase in ozone dose from 0.28 to 0.75 mg/L. This increase in ozone dose resulted in a much less efficient DAF process for removing particles.

5.2.4 Colour and UV_{254} Removal

Similar to alum, PACl adds some colour to the water, but not a significant amount. Figure E6 in Appendix E shows a graph of percent turbidity removal versus percent colour removal in the DAF unit. Similar to alum, there is a positive correlation between the two water quality parameters, however high turbidity removal does not necessarily guarantee high removal of colour. When turbidity removal in the DAF unit was over 60 %, colour removal in the DAF unit ranged from 0 to 80 percent. This figure does not show other factors such as the original raw water colour, or other operating conditions. It should be noted that these values are for apparent colour and not true colour, meaning turbidity interferences have not been removed.

5.2.5 Summary Information

Two graphs in Appendix E, labeled Figure E7 and Figure E8 are shown to represent the effects of ozone on DAF performance and organic matter removal. The raw water turbidity for these runs were 0.40 and 1.10 NTU, respectively. Results show that ozone has only a small effect on particles and turbidity. In Figure E8, an ozone dose of 0.75 mg/L resulted in a decrease in turbidity removal in the DAF unit by 5 percent. Particle removal efficiency decreased by 10 to 20 percent. Still, overall removals were above 80 percent. Overall removals for runs shown in Figure E7 were only around 60 to 70 percent, somewhat lower than results obtained with alum testing or later PACl testing.

As is the alum tests, UV_{254} removal did not follow particle and turbidity removal patterns. Figure E7 shows that the addition of ozone caused an increase in UV_{254} of 25 percent, from 65 to 90 percent. Despite ozone causing a significant decrease in particle removal efficiency for the runs shown in Figure E8, removal of organic matter by adsorption was increased by approximately 3 percent, from 90 to 93 percent. Ozone had different effects on colour, which is primarily removed in the DAF tank. Colour removal more closely followed turbidity and particle removal patterns.

Similar to alum, the dose of PACl is very important for effective removal of particles in the DAF unit (refer to Figure E9). Its importance was not as great when dealing with the removal of UV-absorbing organic matter. Run 1001av used a dose of 10.0 mg/L, while run 1004az was performed at a dose of 4.0 mg/L. This 6.0 mg/L reduction in coagulant dose resulted in a 60 % reduction in turbidity and particle removal. In addition, the coagulant dose was so low, that no UV-absorbing organic matter was removed in adsorption reactions with the coagulant.

Figures E10 and E11 in Appendix E illustrate two examples of the effects of flow change on the performance of the DAF unit. In Figure E10, an increase in flow from 70 to 100 LPM resulted in a sharp decrease in DAF turbidity removal (over 30 percent), however, suspended particles were only slightly affected. The raw water turbidity was 0.33 NTU for these runs. The runs shown on Figure E11 were performed at a time when the raw water turbidity was slightly over 1.0 NTU. In this situation, an increase in the flow from 60 LPM to 90 LPM resulted in very little change in turbidity and only a slight decrease (<15 %) in the number of particles removed. The amount of UV-absorbing organic matter removed remained unchanged despite the decrease in particle and turbidity removal. This is not a surprise as UV-absorbing organic matter is removed before the DAF unit and should not be affected by flow. The coagulant dose was the same for each of these runs. It is not know why the flow did not have the effect on suspended particles in Figure E11 as it did in Figure E10. It has been shown that the DAF unit is not as good at removing particles when the raw water turbidity is less than about 0.40 NTU. Therefore, it is believed that the unit is generally more sensitive to changes in operational parameters at these low particle loading rates. It is also important to place the baffle in the proper position in the flotation tank so a proper air bubble plume can be established.

Similar to runs with alum, flocculator velocity gradient does not have as great an effect on suspended particle removal as the other parameters investigated. Figure E12 in Appendix E shows that a change in flocculator velocity gradient from 40 s^{-1} to 88 s^{-1} resulted in a slight decrease in the number of particles removed in the DAF tank. The higher velocity gradient likely tore apart the floc slightly. The removal of UV-absorbing organic matter was not affected by this change.

5.3 Ferric Chloride

5.3.1 Experimental Conditions

Ferric chloride testing began on December 2, 1999 and was completed on December 14, 1999. Iron salts, such as ferric chloride and ferrous sulfate, tend to be more effective at forming precipitates over a wider range of pH than aluminum salts. Unlike alum and PACl, ferric chloride is a non-aluminum based coagulant. PrarieChem Inc. distributed the ferric chloride solution used for this study. The product was manufactured by Anachemia Science. Ferric chloride is shipped in 20-litre pails as a reddish-brown liquid with a strong odor. The solution is 40% $FeCl_3$ weight per volume with a specific gravity of 1.3. The total iron content of the shipped solution is between 10.0 and 12.4 percent by mass. Ferric chloride is very soluble in water, and therefore does not need to be continuously mixed to maintain homogeneity.

Figures 3.2.1 through 3.2.6 in Section 3.2 show raw water characteristics for the pilot plant study period for turbidity, temperature, pH, UV-absorbance, colour and particles, respectively. In the ferric chloride testing period, turbidity decreased steadily from 0.55 to 0.30 NTU with a corresponding decrease in total particles greater than 2 μm in diameter, from 1309 to 657 particles per milliliter. The water temperature decreased by 1.8 °C from a value of 6.2°C on December 2 to 4.4 °C on December 14. Water is its most dense at 4.0 °C. The organic matter content, as measured by UV-absorbance at a wavelength of 254 nm, decreased from 0.089 to 0.061 cm^{-1}. Surprisingly, the colour remained relatively constant at a range of 27 to 31 ACU. The pH remained constant, as it was throughout the pilot plant study, at approximately 6.5. These values agree with historical data for this period of the year. Raw water quality normally improves during December because most of the easily erodable sediments have been carried through the impoundment earlier in the year when the heavy rains first started. All raw water measurements taken during ferric chloride testing are summarized in Table 5.3.1. The complete raw water data set is located in Table C1 in Appendix C.

Table 5.3.1 Raw water characteristics during Ferric Chloride testing

	Period
	December 2 to December 14
Turbidity (NTU)	0.55 to 0.30 (0.59 max.)
Particles, >2 µm (#/mL)	1309 to 657
Particles, >4 µm (#/mL)	601 to 318
Particles, >8 µm (#/mL)	159 to 103
Particles, >16 µm (#/mL)	2 to 2
Particles, >32 µm (#/mL)	0
Particles, >50 µm (#/mL)	0
Colour (ACU)	28 to 25
UV_{254} (cm^{-1})	0.089 to 0.061
Temperature (°C)	6.2 to 4.4

The pilot plant ran well during the ferric chloride testing period. The only problem was the low concentration ozone monitor that had not been working properly since the beginning of October. Ozone residual measurements were estimated based on previous values on ozone transfer efficiency obtained in this study, and from the literature and the manufactures guide. Ozone transfer efficiency should remain relatively constant at 85 to 95 percent.

5.3.2 Experimental Design Description

The factorial design method of experimentation is the most efficient method of experimentation for the amount and quality of information that results. However, they cannot be performed if a parameter other than the ones being tested, cannot be held constant. Such is the case with the raw water in this study. Normally, a 2^3 design is performed, as it only requires 8 runs to be completed. However, because raw water conditions at the pilot plant were changing daily during the ferric chloride testing program, factorial designs of this size could not be carried out. A series of one-variable-at-a-time experiments were first performed to set the levels for three separate 2^2 factorials, which could each be performed in a two-day period. Some additional, miscellaneous runs were also performed.

Test runs 1202ds, 1202dt, 1202du, 1203dv

Runs 1202ds to 1203dv were performed to establish an optimum coagulant dose for good flocculation and sludge production in the DAF unit. These four runs also helped to establish coagulant testing levels for future experimental runs. The only parameter that was varied for these first four runs was ferric chloride dose, (and soda ash to maintain a constant pH). The coagulant dose varied from 10.0 to 20.0 mg/L. The ozone dose was held constant at 0.0 mg/L. Run 1203dv was abandoned because of a hole in the coagulant dosing tube.

Test runs 1204dw, 1204dx

Once a suitable coagulant dose was established, the amount of soda ash was varied at that coagulant dose to determine its effects on DAF and filter performance. Soda ash doses for runs 1204dw and 1204dx were 16 and 32 mg/L respectively, resulting in a DAF effluent pH of 5.8 and 6.4. The ferric chloride dose was 12.0 mg/L for each run. No ozone was used. Although a one-factor-at-a-time method was used to establish coagulant dose and pH for a factorial design, past results and experience indicate that interaction effects with pH are not very important. This means that the optimum coagulant dose will not change depending on the pH. pH will remain constant for all the factorial designs, and ozone-coagulant dose interactions will be studied in future runs. The soda ash dose required to maintain a pH of above 6.0 for PACl testing was only 5.0 mg/L. This is consistent with the hypothesis that ferric chloride and alum required more pH control than PACl does.

Test runs 1204dx, 1206dy, 1206dz, 1207ea, 1207eb, 1207ec

With knowledge of the behavior of ferric chloride and soda ash in Seymour Impoundment water, a factorial design was established to study the effects of ozone on ferric chloride coagulation. Table 5.3.2 and Table 5.3.3 show factors and levels for two separate 2^2 factorial designs, each with coagulant dose and ozone dose as factors. Six runs labeled 1204dx through 1207ec were performed for these two designs as the coagulant doses for the two designs are the same. Essentially, the following is a 2 X 3 full factorial design, with coagulant dose tested at two levels and ozone dose tested at three levels.

Table 5.3.2 Factorial Design (I) for ferric chloride

	LEVELS	
FACTORS	(+)	(-)
$FeCl_3$ Dose (A), mg/L	16.0	12.0
Ozone dose (B), mg/L	0.75	0.25

Table 5.3.3 Factorial Design (II) for ferric chloride

	LEVELS	
FACTORS	(+)	(-)
$FeCl_3$ Dose (A), mg/L	16.0	12.0
Ozone dose (B), mg/L	0.75	0.00

All other parameters including DAF operating conditions and filtration conditions were held constant. Based on results from alum and polyaluminum testing, ozone dose levels were set at 0.00, 0.25 and 0.75 mg/L.

Test runs 1208ee, 1208ef, 1208eg, 1209ei

With optimum coagulant doses and ozone doses set, DAF operating conditions could be investigated. Again, interactions between chemical doses and flocculation conditions were not studied. Two factors appear to be most significant with respect to the integrated flocculation/DAF unit; flocculation mixing energy and DAF loading rate. DAF loading rate will in turn change the recycle ratio of the saturator. The DAF recycle ratio is the ratio between recycled flow and total flow into the DAF clarifier. If the loading rate increases, the recycle ratio will decrease, unless saturator flow can be adjusted. Based on the literature and the behavior of the flotation process at this facility, recycle ratio does not have significant effect on DAF performance when within the boundaries of change in this design (13 to 20 percent). The 2^2 factorial design for the DAF operation is shown in Table 5.3.4.

Table 5.3.4 Factorial Design (III) for ferric chloride

	LEVELS	
FACTORS	(+)	(-)
DAF Flow (A), LPM	90	60
Velocity Gradient (B), s^{-1}	70	30

Under the above arrangement, mixing energy (Gt) values range from approximately 12,000 to 61,000. For runs where the flow was 90 LPM, 2 stage flocculation was used to further reduce detention time, to approximately 6.5 minutes. Flocculation tank detention time for flows of 60 LPM with three stages is 14.5 minutes. Coagulant doses and ozone doses remained constant at 16 mg/L and 0.25 mg/L, respectfully for these four runs.

Test runs 1208eh, 1209ej, 1210ek, 1213el, 1214em

Runs 1208eh and 1209ej through 1214em were performed to investigate long term filter performance. The main parameters investigated were ozone dose and coagulant dose. Experimental conditions for these five runs are summarized below in Table 5.3.5.

Table 5.3.5 Experimental conditions, ferric chloride long runs

	Run				
	1208eh	1209ej	1210ek	1213el	1214em
Alum dose (mg/L)	16.0	12.0	12.0	12.0	16.0
Ozone dose (mg/L)	0.29	0.00	0.30	0.00	0.32

Table C2 in Appendix C, summarizes the experimental conditions for all ferric chloride runs. This table includes settings and conditions for the ozonation, coagulation, flocculation, floatation and filtration unit processes. Also included is backwash information and run start time and number. Section 5.3.3 presents the results of all of the experimental runs, grouped in the same way as Section 5.3.2. Table C3 in Appendix C summarizes the results for all runs performed with ferric chloride as the coagulant.

5.3.3 Presentation of Results

Test runs 1202ds, 1202dt, 1202du, 1203dv

Table 5.3.6 shows results for the one-variable-at-a-time analysis to determine coagulant dose levels for ferric chloride experiments. Run 1203dv is not shown as it was abandoned due to equipment problems.

Table 5.3.6 Experimental results, runs 1202ds, 1202du, 1202dt

Response Variables	(1202ds)	(1202du)	(1202dt)
Ferric Chloride dose (mg/L)	10	15	20
DAF turbidity reduction (%)	6	27	-247
DAF urbidity (NTU)	1.99	1.12	3.96
DAF particle reduction, >2 µm (%)	12	31	-188
DAF particle reduction, >4 µm (%)	19	41	-291
DAF particle reduction, >8 µm (%)	27	43	-467
DAF colour removal (%)	-8	31	-
UV_{254} removal after coagulation (%)	-26	74	27
Post-DAF UV_{254} (cm^{-1})	0.061	0.011	0.210

* run 1203dv abandoned (no data gathered)

Coagulant dose suitability was based entirely on DAF performance for the removal of turbidity and particle removals. Removal of organic matter as measured by UV-absorbance and colour are not always good indications of DAF performance. Ferric chloride adds a lot of colour to the water and DAF effluent colour was therfore very high when compared to results with alum and PACl testing. In most of the ferric chloride runs, colour was increased from a raw water value of approximately 30 ACU to over 80 ACU after the coagulant was added. With alum and PACl, there was no increase in colour after the addition of the coagulants. Because DAF effluent colour is so high, the process relies heavily on the filters to remove the rest of the colour. As seen with alum and PACl, most of the organic material as measured by UV-absorbance is removed via absorption processes at the point of coagulant addition. Therefore, removal in the DAF unit is generally low and not representative of its true efficiency.

The purpose of the preceding runs was to establish coagulant levels for factorial design analyses. Referring to Table 5.3.6, it is obvious that a ferric chloride dose of 15 mg/L for these raw water conditions yielded the most favorable results. UV-absorbance was very low in the DAF effluent, which indicates a suitable coagulant dose for the absorption of organic matter onto coagulant particles and reaction products. Despite this, turbidity removal for run 1202du was poor when compared to other coagulants. Turbidity removals at optimum conditions for alum and PACl were as high as 85 percent, while the best removal efficiency for ferric chloride was 27 %. However, as will be seen later in this section, DAF turbidity and particle removal efficiencies improved at this dose. This indicates that another factor, likely a poorly functioning saturator, was to blame for the low removals for these three runs. Upon addition of ferric chloride, turbidity and particles in the water rose 200 to 600 percent. This is compared to values usually less than 100 percent for alum and PACl.

Test runs 1204dw and 1204dx

Runs 1204dx and 1204dw were performed to determine the proper soda ash dose and subsequent pH that would be used for the remaining runs in the ferric chloride testing phase. Soda ash doses of approximately 32 and 16 mg/L were used, which resulted in the pH of the water (after soda ash and coagulant addition) of 6.4 and 5.8, respectively. Table 5.3.7 summarizes DAF results for these two runs.

Table 5.3.7 Experimental Results for soda ash testing

Response Variables	(1204dx)	(1204dw)
Soda Ash dose (mg/L)	32.0	16.0
DAF turbidity reduction (%)	56	48
DAF turbidity (NTU)	1.03	0.96
DAF particle reduction, >2 µm (%)	32	23
DAF particle reduction, >4 µm (%)	51	40
DAF particle reduction, >8 µm (%)	58	42
DAF colour removal (%)	25	29
UV_{254} reduction after coagulation (%)	79	83
Post-DAF UV_{254} (cm^{-1})	0.016	0.011
pH	6.4	5.8

No repetitions were performed for these two runs. With respect to turbidity reduction and particle removal, coagulation and flocculation performed better at a pH of 6.4 than at 5.8. Post-DAF UV_{254} and colour removals are nearly the same for each run. It should also be noted that the coagulant dose for these two runs was 12.0 mg/L. This dose yielded much better results than a dose of 10.0 mg/L or 15.0 mg/L for runs 1202ds and 1202du, respectively, as discussed in the last sub-section. This may perhaps be due to better DAF saturator operation, or, most likely, a dose of 12.0 mg/L is optimum for the water quality seen at this time. Regardless, the effectiveness of DAF for decreasing turbidity when ferric chloride is used still appears to be much poorer than for other coagulants. Particle count removal is also much poorer with ferric chloride than for alum or PACl.

Test runs 1206dy, 1206dz, 1207eb, 1207ec

Three 2^2 factorial designs were performed with ferric chloride to investigate the effects of coagulant dose, ozone dose, flocculation time and flocculation energy on a number of DAF performance parameters. The performance of the DAF will indicate the efficiency of the flocculation process. Information gathered from the results of the factorial design analysis will help the author determine which factors have the greatest effect, or are the most significant, in relation to the efficiency of the treatment process and specifically the DAF unit. Each factorial design will be analyzed separately in its own section.

Table 5.3.2 in Section 5.3.2 shows the factors and parameters for the first factorial design performed. A table of results for the first factorial design performed for ferric chloride runs is located below, labeled Table 5.3.8.

Table 5.3.8 Results, ferric chloride factorial design (I)

Response Variables	(1206dy)	(1207eb)	(1206dz)	(1207ec)
DAF turbidity reduction (%)	-32	66	-12	47
DAF particle reduction, >2 mic (%)	28	-6	4	-72
DAF particle reduction, >4 mic (%)	42	13	26	-8
DAF particle reduction, >8 mic (%)	54	23	37	21
DAF color removal (%)	0	50	14	40
UV_{254} reduction after coagulation (%)	74	91	74	89
DAF UV_{254} removal (cm^{-1})	0.018	0.000	0.015	0.000
DAF UV_{254} (cm^{-1})	0.005	0.007	0.008	0.009

Factorial design analysis for a 2^2 design is performed in the same way as for a 2^3 design. The design matrix (table of signs) for the factorial design is located below in Table 5.3.9. Turbidity is the only response variable that is shown, however, particles, colour and UV-absorbance responses to changes in the factors will be shown later.

Table 5.3.9 Table of signs, ferric chloride factorial design (I)

		Main Effects		Interactions	
Run #	Mean	A (Coagulant Dose)	B (Ozone Dose)	AB	Turbidity
1 (1206dy)	1	-1	-1	1	-32
2 (1207eb)	1	1	-1	-1	66
3 (1206eb)	1	-1	1	-1	-12
4 (1207ec)	1	1	1	1	47
Divisor	4	2	2	2	

Main effects and interactions are tabulated below in Table 5.3.10.

Table 5.3.10 Main effects and interactions for ferric chloride factorial design (I)

	DAF Percent Reduction					
Main Effects	Turbidity	Particles, >2	Particles, >4	Particles, >8	Colour	UV_{254} (post-coag)
$FeCl_3$ dose, A	39.1	-27.2	-15.7	-11.9	18.9	8.2
Ozone dose, B	0.2	-22.7	-9.2	-4.6	1.1	-0.5
Interactions	Turbidity	Particles, >2	Particles, >4	Particles, >8	Colour	UV_{254} (post-coag)
AB	-9.8	-10.7	-1.2	3.9	-6.1	-0.7

The value of the main effect of a variable measures the average effect of that variable over all conditions of the other variables. Interaction effects are calculated as the difference between the average effect of factor A with one level (+) of factor B and the average effect of factor A with the other level (-) of factor B. With only a 2^2 design, it may be difficult to analyze the results in the table, as there are only 3 effects for each response variable (eg. turbidity). However, it seems apparent that factor A, or the coagulant dose, is much more significant than the effect of ozone alone, at these levels. It has already been concluded that ozone doses in excess of those set as the levels for this design have deleterious effects on the formation of floc particles in the DAF tank. To obtain a better picture of the significance of the factors on each of the response variables, normal probability plots are normally produced. However, because there would only be 3 points plotted on each diagram, they were not produced for this analysis.

What is interesting with these data is that even with a 66 percent reduction in turbidity for run 1207eb, there was very little reduction of particles. Upon the addition of the ferric chloride coagulant, particles increase by more than 100 %, much higher than values seen for alum or PACl. It should also be noted that these tests occurred when the water temperature was less than 6°C, which may affect the performance of the DAF process for removing particles. For runs 1207eb and 1207ec, where turbidity reduction in the DAF unit was 66 and 47 percent, respectively, colour was reduced by 50 and 40 percent, respectively. Therefore, it can be said that apparent colour contributes significantly to the turbidity when ferric chloride is used. Thus, the relative significance of particles on the turbidity is reduced. From these results, it is clear that a coagulant dose of 16.0 mg/L is much better than a dose of 12.0 mg/L for removing particles. It appears that ozone, at the levels tested, did not significantly affect flocculation.

Test runs 1204dx, 1206dz, 1207ea, 1207ec

Table 5.3.3 in Section 5.3.2 shows the factors and parameters for the second factorial design with ferric chloride. The design is the same as the first one, except with ozone doses of 0.75 and 0.00 mg/L, instead of 0.75 and 0.25 mg/L. A table of results for the second factorial design performed for ferric chloride runs is located below, labeled Table 5.3.11.

Table 5.3.11 Experimental Results (II), ferric chloride testing

Response Variables	(1204dx)	(1207ea)	(1206dz)	(1207ec)
DAF turbidity reduction (%)	56	74	-12	47
DAF particle reduction, >2 µm (%)	32	42	4	-72
DAF particle reduction, >4 µm (%)	51	52	26	-8
DAF particle reduction, >8 µm (%)	58	52	37	21
DAF colour removal (%)	25	65	14	40
UV_{254} reduction after coagulation (%)	79	94	74	89
Post-DAF UV_{254} (cm^{-1})	0.016	0.005	0.008	0.009

The design matrix (table of signs) for this factorial designs is located below in Table 5.3.12. As with the previous factorial design, only the turbidity response variable is shown.

Table 5.3.12 Design Matrix for ferric chloride factorial design (II)

		Main Effects		Interactions	
Run #	Mean	A (Coagulant Dose)	B (Ozone Dose)	AB	Turbidity
1 (1204dx)	1	-1	-1	1	56
2 (1207ea)	1	1	-1	-1	74
3 (1206dz)	1	-1	1	-1	-12
4 (1207ec)	1	1	1	1	47
Divisor	4	2	2	2	

The main effects and interactions are tabulated in Table 5.3.13 below for all response variables.

Table 5.3.13 Main effects and interactions for ferric chloride factorial design (II)

	DAF Percent Reduction					
Main Effects	Turbidity	Particles, >2	Particles, >4	Particles, >8	Colour	UV_{254} (post-coag)
$FeCl_3$ dose, A	19.3	-16.7	-8.2	-5.4	16.4	7.4
Ozone dose, B	-23.8	-35.7	-21.0	-12.6	-8.9	-2.5
Interactions	Turbidity	Particles, >2	Particles, >4	Particles, >8	Colour	UV_{254} (post-coag)
AB	10.0	-21.3	-8.8	-2.6	-3.6	0.1

Normal probability plots were not created for this factorial design. Results for this design differ from previous ferric chloride runs, as well as runs for the other coagulants. Ozone dose has a greater effect on turbidity and particles than ferric chloride dose does at these levels. That is to say, changing the ozone dose from 0.00 to 0.75 mg/L has a greater effect on turbidity and particle removal in the DAF unit than does changing the ferric chloride dose from 12.0 to 16.0 mg/L. This was not seen in the first factorial design, likely because the levels for ozone were more spread out for this design. All other parameters were the same for the two designs. The greatest reduction in turbidity and particles in the DAF unit was for run 1207ea, which used a ferric chloride dose of 16.0 mg/L and no ozone. Turbidity removal was 74 percent, which is closer to the maximum of 85 percent removal seen with PACl and alum testing. Particles were still only reduced by around 50 percent, 30 percent lower than the best runs for alum and PACl. However, these are the best results seen for ferric chloride as a coagulant. The second best run with respect to the removal of suspended solids was run 1204dx, which used a ferric chloride dose of 12.0 mg/L and no ozone. The other two runs did not reduce particle counts or turbidity greatly.

Table 5.3.13 indicates that coagulant dose had the greatest effect on the removal of organic matter in terms of colour and UV-absorbance. However, these average effects were only 16.4 and 7.4 percent, respectively. At either of the levels for ferric chloride and ozone, the UV reduction after coagulation was greater than 74 percent, with 94 percent for run 1207ea being the best. The pattern for colour removal in the DAF unit is the same as for removal of turbidity. The best removal rate was for 1207ea, at a value of 65 percent, while the lowest occurred with the lowest removal of turbidity. This occurred when the ferric chloride dose was high, and the ozone dose was low.

Test runs 1208ee, 1208ef, 1208eg, 1209ei

The third and final factorial design for ferric chloride had DAF flow and flocculator velocity gradient as factors. Results from the DAF unit are shown below in Table 5.3.14.

Table 5.3.14 Results for ferric chloride factorial design (III)

Response Variables	(1208eg)	(1208ee)	(1209ei)	(1208ef)
DAF turbidity reduction (%)	67	57	65	59
DAF particle reduction, >2 µm (%)	-32	31	-94	8
DAF particle reduction, >4 µm (%)	-25	53	-71	33
DAF particle reduction, >8 µm (%)	-17	62	-38	43
DAF colour removal (%)	38	31	44	46
UV_{254} reduction after coagulation (%)	80	82	87	82
DAF UV_{254} (cm^{-1})	0.016	0.013	0.010	0.012

The table of signs for this problem is located below in Table 5.3.15. Turbidity is the only response variable shown in this table.

Table 5.3.15 Table of signs for ferric chloride factorial design (III)

		Main Effects		Interactions	
Run #	Mean	A (DAF Flow)	B (Velocity Gradient)	AB	Turbidity
1 (1208eg)	1	-1	-1	1	67
2 (1208ee)	1	1	-1	-1	57
3 (1209ei)	1	-1	1	-1	65
4 (1208ef)	1	1	1	1	59
Divisor	4	2	2	2	

Main effects and interactions calculated from the above table of signs are shown below in Table 5.3.16.

Table 5.3.16 Main effects and interactions for ferric chloride factorial design (III)

	DAF Percent Reduction				
Main Effects	Turbidity	Particles, >2	Particles, >4	Particles, >8	Colour
DAF Flow, A	-4.2	41.1	45.2	40.0	-0.9
Flocculator G, B	-0.1	-21.1	-16.4	-9.7	5.3
Interactions	Turbidity	Particles, >2	Particles, >4	Particles, >8	Colour
AB	1.1	9.8	6.6	0.5	2.2

Similar to previous results, the DAF loading rate (factor A) has the greatest effect on the removal of particles by flotation. Decreasing the DAF flow rate from 90 to 60 LPM, results in an average 40 percent increase in the particle removal in the DAF tank. Although DAF flow had a greater effect on turbidity removal than flocculator velocity gradient, it was not large compared to particle removal. Increasing the velocity gradient in the floc basins from 30 to 70 s^{-1} resulted in an average increase of particles removed in the DAF unit by 20 percent. This increase in velocity gradient had an opposite effect on the removal of colour from the water. It is interesting to see that the runs with a flow of 60 LPM resulted in the best turbidity removal, whereas the runs with a flow of 90 LPM resulted in the best particle removal. This behavior has not been seen before. DAF flow and velocity gradients had little effect on the removal of colour and UV-absorbing organic material from the water.

Test runs 1208eh, 1209ej, 1210ek, 1213el, 1214em

Table 5.3.17 shows results for the final five runs of ferric chloride testing. These runs were all performed overnight so that filter performance could be studied. Filter run length is the number of hours that the filter effluent turbidity remained below 0.1 NTU from the start of the run.

Table 5.3.17 Results for ferric chloride long runs

Response Variables	1208eh	1209ej	1210ek	1213el	1214em
DAF turb reduction (%)	67	66	45	74	68
DAF particle reduction, >2 µm (%)	-23	41	-5	-	27
DAF particle reduction, >4 µm (%)	-2	52	26	-	30
DAF particle reduction, >8 µm (%)	10	53	38	-	34
DAF colour removal (%)	39	38	25	50	48
UV_{254} reduction after coagulation (%)	90	87	77	93	93
Post-DAF UV_{254} (cm^{-1})	0.008	0.009	0.016	0.005	0.007
Filter run length (hr)	N/A	7.0	N/A	>11.0	15.0

The runs with the best particle reduction (1209ej, 1213el (assumed), and 1214em) resulted in the best filter effluent quality. Similar to previous runs with ferric chloride, reduction in turbidity does not necessarily mean high particle removal. Much of that turbidity reduction is likely due to colour removal. Runs 1208eh and 1214em were run under the exact same conditions, with an ozone dose of approximately 0.30 mg/L and a ferric chloride dose of 16.0 mg/L. However, despite having essentially the same reduction in turbidity in the DAF unit, only run 1214em had good particle reduction (27 percent versus –23 percent for particles greater than 2 μm). As a result of this, run 1214em had a 15.0 hour filter run where the turbidity stayed below 0.1 NTU. This difference in results is likely due to the fact that the raw water turbidity decreased by 18 percent and particle counts greater than 2 microns in diameter decreased by 22 percent. It is likely that the ferric chloride dose was more optimized for the raw water quality on December 14 than on December 8.

Runs 1209ej and 1213el were performed under the same conditions, with a ferric chloride dose of 12.0 mg/L and no ozone. Both runs had good turbidity reductions and long filter runs. Run 1213el had better turbidity reduction, but no particle data were available. Its filter run was much longer than that of 1209ej. Data were only gathered for 11 hours, however, although turbidity was not rising, it appeared particles were starting to break through when the run was ended. Raw water quality was approximately 20 percent better with respect to particles and turbidity for run 1213ej than for 1209ej. This likely explains why the run produced better quality DAF effluent and a longer filter run. Run 1210ek was the same as the previous two, but with 0.30 mg/L of ozone. It is obvious that even this small dose of ozone had deleterious effects on the quality of the water in the DAF effluent. Turbidity reduction was only 45 percent and particle reduction was poor, resulting in filter run than never produced effluent that had a turbidity less than 0.1 NTU.

5.3.4 Colour and UV_{254} Removal

Ferric chloride adds much more colour to the water than either alum or PACl. The colour immediately after coagulant addition went up approximately 50 ACU to over 80 ACU when ferric chloride was used. Normally, colour rose by approximately 5 units when alum or PACl was used as the coagulant. Like alum, there is a strong positive correlation between turbidity and colour removal in the DAF unit, as seen by Figure F1 in Appendix F. Colour removal rates range from 40 to 65 percent when the turbidity removal in the DAF unit is above 60 percent. These rates are lower than what were seen with either alum or PACl.

As seen in Figure F2 in Appendix F, there is a positive correlation between turbidity and UV_{254} removal rates with ferric chloride coagulation. However, even when turbidity removal rates in the DAF unit are below 50 percent, UV_{254} removal by absorption range from 75 to 90 percent. When turbidity removal is higher, UV_{254} removal reached 94 % prior to DAF.

5.3.5 Summary Information

Referring to the general discussions previously presented, it is clear that ferric chloride did not perform as well at removing particles as did alum or polyaluminum chloride. In addition, ferric chloride adds a lot of colour to the water, which cannot all be removed in the DAF unit. Figure F3 in Appendix F shows that the turbidity was reduced by 75 % in the DAF unit when no ozone was used. However, when an ozone dose of 0.25 mg/L and 0.75 mg/L was added, turbidity reduction dropped to 66 and 47 percent, respectively. Particle removal was lower than turbidity removal with rates of 42 percent for particles greater than 2 μm in diameter, when no ozone was added. The addition of ozone further decreased particle removal. Colour was reduced by 65 percent with just a coagulant, and this removal level was reduced slightly when ozone was added. Similar to previous results, UV-absorbance was removed very well, irrespective of the ozone dose. 94 percent of UV-absorbing organic matter were removed prior to the DAF tank, regardless of the ozone dose, even though ozone substantially affected particle removal.

Ferric chloride dose, like all coagulants, had a strong effect on suspended particle and colour removal in the DAF tank. A decrease of 4.0 mg/L resulted in a decrease in turbidity removal of nearly 20 percent and a decrease in the removal of particles greater than 2 µm in diameter of 10 percent (refer to Figure F4 in Appendix F). Larger particles were not affected as much as the smaller particles. They are generally removed more efficiently in the DAF process than smaller particles are. There was also a 35 percent decrease in colour removal as a result of the change in coagulant dose. The removal of UV-adsorbing organic matter was only slightly affected by the decreased dose. Its removal was very good at 94 percent.

Figure F5 in Appendix F shows that an increase in DAF flow from 60 to 90 LPM resulted in very little change in turbidity and colour removal in the DAF unit, however it did result in a significant increase in particle removal, by as much as 60 percent. These particle results are contrary to what was seen with alum or PACl. Reynolds and Richards, (1996) state that ferric chloride forms a very dense, rapid settling floc. It is possible that these floc particles are detaching from the air bubbles.

Consistent with previous results, flocculator velocity gradient did not greatly affect the performance of the DAF unit and the absorption of organic matter (Figure F6, Appendix F). This again demonstrates the robustness of the DAF performance with respect to its operational parameters.

5.4 Filtration Results

The SCADA system on the control computer in the pilot plant lab continuously logged filter effluent turbidity and particle count data for the entire pilot plant study. Three filters were run continuously for all 153 runs performed for the study. For each run and each filter, a file containing filter effluent turbidity, particle counts, filter flow and headloss was saved. Therefore, there are 459 filter data files that were compiled throughout the pilot plant study. To present these data would not be within the scope of this thesis, and therefore only a brief overview of the results will be presented.

Table C3 in Appendix C shows filter run data and for all runs performed for this study. For some runs, grab samples were analyzed in the lab for turbidity, particles, UV_{254}, and colour. On-line particle count data were only recorded in this table when the turbidity of the filter effluent maintained a value of less than 0.1 NTU for a period of greater than 2 hours, thereby achieving the filter effluent goals set out in the objectives of the study. A time of two hours also eliminated the chance that the filter effluent turbidity dropped below 0.1 NTU for reasons other than good treatment conditions. In many cases, run lengths were less than two hours, therefore these data were not recorded. The values for particle counts that were recorded in the table were the lowest values during the period that the filter turbidity was below 0.1 NTU.

The quality of the effluent from the DAF unit is an important factor for the performance of filters. In general, the better quality that the DAF effluent is, the longer the filter runs. This is because the filters will not clog as quickly as when there are more particles in the filter influent. This is a major reason why advanced treatment has such a large advantage over direct filtration. A proper coagulant dose is just as important for filter performance as it is for DAF performance. Of the 56 runs where the DAF unit reduced turbidity by greater than 50% (and filter data was recorded), regardless of the absolute value of the turbidity, 50 of those runs produced filter effluent turbidity less than 0.1 NTU. The six runs that did not were all from ferric chloride testing. The average number of particles in the 2 to 3 micron size range, as recorded by the on-line particle counter for these 50 runs, was 1.2 particles per milliliter. Values ranged from 5 particles to 0 particles per milliliter. In all 50 of these runs, particle removal was greater than 2-log. Of the remaining 93 runs that were performed and where DAF removed less than 50 percent of the turbidity, only 10 filter runs produced effluent turbidity of less than 0.1 NTU.

6.0 Conclusions

The primary objective identified at the beginning of the Seymour pilot plant study was to investigated numerous water treatment unit processes to improve drinking water quality for Vancouver area residents. Specifically, the purpose of the study was to investigate an advanced treatment process train (DAF instead of sedimentation) along with pre-ozonation to aid in the flocculation of particles and removal of organic matter. The plant was equipped with a 3-stage flocculator integrated with a DAF unit. Most of the measurements taken for this study were done so with the objective of evaluating DAF performance. How many particles are removed in the DAF unit is indicative of the quality and efficiency of flocculation.

It is clear from the results for all phase of this study (alum, PACl and $FeCl_3$ testing), that an advanced treatment process with a DAF process for solid-liquid is very effective at removing turbidity causing particles and organic matter before the filters. This provides an additional barrier when compared to a direct filtration process. Conventional treatment was not a feasible option for treating Seymour impoundment water, because the water has low turbidity and low density particles. Emphasis during this study was placed on the effectiveness of DAF at removing particles and colour from the water. These results highlight the importance of the use of DAF and multi-barrier treatment approaches in general, for treating water quality types seen at Mount Seymour.

The use of ozone as a coagulant aid was the second major objective of this study. The effectiveness of ozone as a coagulant aid on Seymour impoundment water was certainly affected by the quality of the raw water. When raw water turbidity was low, with corresponding low organic matter content, even small doses of ozone (as low as 0.25 mg/L) had negative effects on the flocculation of particulate matter. In fact, irrespective of the raw water quality, high ozone doses (greater than 1.0 mg/L) had negative effects on the flocculation process. However, when the raw water quality began to deteriorate near the end of October, and particle and organic matter levels rose, the effect that ozone had on particles and organic matter changed. At low doses, pre-ozonation did not have the extreme negative effect on particle removal that it had previously. For most runs, ozone either slightly increased or slightly decreased particle and colour removal in the DAF unit. There were only a few runs where ozone increased particle removal by DAF by more than 10 percent. However, the benefits of ozone for reducing and converting UV-absorbing organic matter were much more significant.

Due to new EPA regulations and concern over the formation of disinfection by-products, the removal of organic matter prior to the injection of a disinfectant has become a priority for many water utilities around the world. Organic matter also causes taste and odour concerns in the water, as well as decreasing its aesthetic appearance by changing its colour. The treatment process used in the Seymour study was generally very effective at reducing organic matter from the water. Most of this removal occurred via adsorption reactions to coagulant precipitates immediately after coagulant injection (upstream of the flocculation and DAF units). Up to 90 percent reduction of UV-absorbing organic matter (non-colour causing) was obtained with this mechanism. Very little additional reduction was accomplished by flotation in the DAF unit. There appeared to be a minimum amount of coagulant that needed to be added for adsorption of organic matter onto coagulant precipitates. Without this, the organic matter had nothing to bond to, and therefore its reduction was poor. When particle removal was optimized in the DAF unit, organic matter removal by adsorption immediately after coagulant injection was very good. This indicates that the optimum coagulant dose for particle destabilization is the same as for organic matter removal. However, even when particle removal was not optimized, organic matter removal was good, particularly when ozone was used. Even if ozone caused a large decrease in particle reduction in the DAF unit, UV-absorbing organic matter was still efficiently removed. The removal of colour from the water occurred primarily in the DAF unit and was more related to turbidity removal than UV-absorbance removal was.

Five primary objectives were established at the beginning of the study. Each one of these will be discussed and evaluated in more detail, below.

(1) Evaluate the effects of different coagulants on the flocculation of turbidity causing particles.

Alum, polyaluminum chloride and ferric chloride were the coagulant chosen for this study. Because there was no control over the quality of the raw water, conditions under which the coagulants were tested varied. Alum and PACl were tested at two different times of the year, under different water conditions. Ferric chloride was only tested in December, where the water was cold and the turbidity was decreasing to levels below 0.40 NTU.

Because there was no analytical method used to evaluate particle destabilization for this study, (such as zeta potential), flocculation was evaluated based on the effectiveness of DAF at removing particles and turbidity. Alum and PACl performed well at reducing particle counts. Turbidity removal of up to 80 percent could be achieved when the alum or PACl dose was properly optimized. Results also indicate that the DAF process is better at removing particles when the raw water quality deteriorates. Turbidity removal early in the study, when raw water turbidity was below 0.25 NTU, was not as good as when the raw water turbidity was worse later in the study. Still, removal rates in the DAF where over 70 percent even when the quality of the water was good. These removal rates are not compared to the raw water, but isolated to the DAF/flocculation unit itself, since along with coagulant addition comes an increase in colloidal particles. Very little difference could be found between alum and PACl at removing particles. However, previous studies have shown that PACl is more effective at lower temperatures than either alum or $FeCl_3$. Not enough data could be acquired during this study to support that claim. However, one distinct advantage that PACl has over alum is its effect on the pH of the water. PACl was fairly effective even when no soda ash was added to the water, although approximately 5.0 mg/L was added to keep the pH at optimum levels and optimize coagulation. Conversely, alum requires the addition of a lot more soda ash than PACl does.

The removal of particles in the 2 to 32 μm size ranges followed similar trends as turbidity removal. The better the turbidity removal in the DAF unit, the better the reduction in particles. Generally, the removal of particles greater than 2 μm was 0 to 10 percent better than turbidity removal. Larger sized particles were removed even better in relation to turbidity and smaller particles. The particles size ranges of >16 μm, >32 μm and >50 μm were not analyzed as there were very few particles in these size ranges in the water and therefore removal rates in the DAF would not be particularly indicative of its true performance.

Ferric chloride was not as effective a coagulant as alum or PACl were. Although the removal of UV-absorbing organic matter was good or even better than with PACl or alum, the best turbidity removal that could be obtained with $FeCl_3$ was 75 percent although most runs were below 70 percent. Particle removal was also poorer with ferric chloride than with the other coagulants. Like alum, ferric chloride requires the addition of more soda ash than PACl does to maintain the water's pH at an optimum operating range for coagulation to occur. Ferric chloride also adds a lot of colour to the water. This effect will be investigated later on in the discussion.

(2) Evaluate the effects of pre-ozonation on the flocculation of particles.

Depending on the raw water quality, ozone had a negative or positive effect on the flocculation of particles and subsequent DAF performance. When the raw water turbidity and organic matter content were low at the beginning of the study, ozone doses, even as low as 0.25 mg/L, had a negative impact on the removal of particles and turbidity by the DAF unit. With alum as the coagulant and a raw water turbidity of approximately 0.20 NTU, an ozone dose of 0.25 mg/L caused a drop in turbidity removal of 15 percent compared to treatment with alum alone. A dose of 0.50 mg/L caused a drop of 35 percent compared to treatment with alum alone. However, when the turbidity and organic matter content started to increase, results were different. When the raw water turbidity was 0.40 NTU, an ozone dose of 0.25 mg/L caused an increase of turbidity and particle reduction of a little less than 10 percent compared to when no ozone was used. An addition 0.25 mg/L of ozone caused the turbidity removal to decrease slightly when compared to treatment with just 0.25 mg/L of ozone. Although these effects are not large and the increase in turbidity removal may partly be due to randomness, the fact that there was not a significant decrease in turbidity removal in the DAF is important. Results later on in the study with alum and PACl give similar results. That is to say there is little to no increase in particle removal in the DAF unit when low doses of ozone are used. As previously mentioned, higher ozone doses (>1.0 mg/L in most cases) cause a certain decrease in suspended particle removal in the DAF unit, regardless of the raw water turbidity.

Even though there appears to be no advantage for particle removal in the DAF unit with ozone in terms of percent reduction, the particle size distribution diagrams for alum (located in Appendix D) show that ozone decreases the particle loading to the DAF unit. When a coagulant is added to the water, the number of particles in that water increased, because of the composition of the coagulant, effectively increasing the particle loading rate to the DAF. When ozone is used with the coagulant, the increase in particles due to coagulant addition is not as great, thereby decreasing the loading rate to the DAF unit compared to when no ozone was used. However, the number of particles going into the DAF unit is still larger than what the raw water had. Therefore, even if the percent removal of particles in the DAF unit is the same with and without a small ozone dose, the actual number of particles in the DAF effluent is less. This means that there will be a smaller particle loading rate being delivered to the filters.

Ozone has a much larger negative effect on ferric chloride coagulation. With the addition of only 0.25 mg/L of ozone, particles greater than 2 μm in diameter were not decreased at all, compared to 40 percent reduction when no ozone was used. The effect of ozone on turbidity reduction was not as great, indicating that colour has a strong influence on the turbidity of the water with ferric chloride. Turbidity removal percentages were only reduced by approximately 10 percent.

(3) Evaluate the effects of ozone dose and coagulant type and dose on organic matter removal.

The amount of organic matter in the DAF unit was evaluated based on two analytical measures: colour and UV-absorbance. As previously discussed, each one of these analytical techniques detect different types of organics and therefore their removal mechanisms will not be the same.

Colour is caused by the presence on natural metallic ions (such as when ferric chloride is added to the water), humus and peat materials, plankton and other aquatic organisms. For the Seymour pilot study, the apparent colour remained near a value of 25 ACU. Turbidity was not removed for colour measurements, as its effects are small at the turbidity levels seen for the pilot study. Colour was primarily removed in the DAF tank by flotation to the surface. Colour data were not available for most of the alum testing, however, colour removal in the DAF with PACl and $FeCl_3$ was normally around 60 percent when the coagulant dose was optimized based on turbidity and particle removal. Values were as high as 70 percent with PACl. Ferric chloride was generally less effective at removing colour than PACl. In addition, ferric chloride adds a lot of colour to the water. At the coagulant doses being used for $FeCl_3$ (12.0 to 16.0 mg/L), the colour rose to above 80 ACU from values under 30 ACU for the raw water. Therefore, even if colour removal in the DAF unit was just as good with $FeCl_3$ than with PACl, there would still be a lot of colour going to the filters. The small amount of data for colour removal with alum indicate that results are comparable or even better than when PACl is used.

It is clear that UV-absorbing organic matter, as measured at a wavelength of 254 nm, is removed via adsorption onto coagulant precipitates. Those organics that most strongly absorb UV-light are lignin, tannin, humic substances and various aromatic compounds. Removal of UV-absorbing organic matter via adsorption was up to 90 percent in some runs. The DAF unit did not add to the removal of organic matter. When there was high removal of particles in the DAF unit, there was high organic matter removal by adsorption. However, even if particle removal was not good, organic matter removal was still good. This indicates that the critical amount of coagulant required for the removal of particles in the DAF unit is more than the critical amount of coagulant required for the removal of UV-absorbing organic matter. There is little difference in the removal of organic matter when different coagulants are used.

It appears ozone had more of a positive effect on the removal of organic matter than it had for the removal of particles and turbidity. Ozone normally enhanced organic matter removal by 10 percent, but even more significant was the improved removal of organic matter when particle removal decreased. Even when ozone had negative effects on particle and turbidity removal in the DAF tank, the removal of organic matter stayed the same or even improved.

(4) Evaluate the effects of flocculation and DAF operating conditions on clarification performance.

Flocculation velocity gradient, tapered flocculation, flocculation detention time, DAF loading rate, DAF recycle ratio and DAF saturator pressure were all parameters that could be varied at the Seymour pilot plant. For the purpose of this study, DAF saturator pressure was held constant at approximately 480 kPa. A change in the flow of water into the flocculation/DAF unit changed the detention time in the flocculators as well as the loading rate into the DAF unit. In addition, the increased loading decreased the recycle ratio, assuming that the saturator flow remained constant.

Under the conditions tested during the pilot plant study, the effects of velocity gradient and DAF loading rate were minimal when compared to the effects of coagulant and ozone dose. The DAF process was particularly robust with respect to flocculator velocity gradient and recycle ratio. Recycle ratio changed when the flow changed, however, it is believed that any changes caused by the change of flow into the DAF tank is due to changing flow patterns in the flotation cell and not due to the change in recycle ratio. It appears that there was no change in DAF performance when tapered flocculation was used. Similarly, three stage versus two stage flocculation had no effect on DAF effluent quality.

The flow of water through the flotation cell did have an effect on the quality of the DAF effluent. Increasing the flow through the flocculation/DAF unit decreases flocculation time and the time allowed for particles to float to the surface of the flotation cell. Flocculation time as low as 5 min have been found to be quite suitable for the aggregation of particles prior to DAF, therefore the change in DAF effluent quality is likely due to the change in flow through the flotation cell, (Edzwald, 1995). For alum and PACl, and increase in flow resulted in poorer DAF performance. At these flows the DAF loading rate was near 10.0 m/hr. This is not a very large loading rate, and therefore the decrease in DAF effluent quality as measured by turbidity and particles is likely due to a change in the way the plume of air bubbles spread out in the DAF tank. At higher flows, the plume was much more dispersed, causing some particles to be pushed to the bottom of the clarifier and into the DAF effluent line. With $FeCl_3$, the results were opposite, meaning better quality DAF effluent was produced when higher flows in the DAF unit were used. However there is no reasonable explanation for this behavior.

(5) Study the effects of DAF on filter performance.

The results from this pilot study strongly indicate the importance of some sort of pretreatment before filtration. The results show that DAF is very effective at removing particles, turbidity and colour from the water. Because there are fewer particles in the water in the filter influent, the filter runs would be expected to last longer and create better quality effluent. As indicated in Section 5.4, 100 percent of the filter runs that treated DAF effluent that had greater than 50 % particle removal, resulted in effluent with turbidity lower than 0.1 NTU. Not only is turbidity reduced in filter effluent, but also particles and the risks of contamination by microbial pathogens. When turbidity removal in the DAF unit was less than 50 percent, only 13 percent of filter runs resulted in turbidity effluent less than 0.1 NTU. Although previous GVRD studies performed at the pilot plant indicate than direct filtration does reduce particles and organic matter effectively, filter runs are much shorter. And by using a multi-barrier approach, water utilities have the additional security against contamination of the public drinking water supply.

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Appendix A – Pilot Plant Operation Manual

The Seymour Pilot Plant was constructed at the beginning of the 1990's to conduct tests for GVWD's Drinking water treatment program. The pilot plant building has a footprint of 7.3 m by 14.6 m, and is located next to the chlorination building at the base of the Seymour Falls Dam. The main level includes a 7.3 m by 3.7 m lab at its South end. The sludge handling facilities, workbench, ozone equipment, ozone columns, filter columns, and coagulant storage tanks are also located on the main floor. Above the lab is the pilot plant's mezzanine level where the DAF unit, flocculators and access to the top of the filter columns are located. At the South end of the building is a fenced area, which holds the propane tank for heating the building, and two large water storage tanks for additional testing purposes. In addition, this area has a large supply of spare PVC parts and filter media.

Raw water supply

The raw water for the pilot plant comes directly from the Seymour water storage impoundment. The water enters the plant via a 50 mm or 75 mm line. A main line travels from the impoundment through the chlorine building where a shut off valve and two pumps (5.6 kW and 7.5 kW) are housed. Between the chlorine building and the pilot plant is an underground access point where the pipe splits to a 50 mm line and a 50 mm line. The water entering the pilot plant may not be completely representative of the water in the reservoir because of the detention time in the piping system. The raw water sample port for the 75 mm inlet line, which is used more often than the 50 mm line, is located in the northwest corner of the building.

Ozonation

Ozone generation and transfer to the water occurs at the pilot plant using a 1 kg/day capacity ozone generator. Three groups of 2 ozone columns are used to ensure adequate contact time. Raw water flows down the first column as ozonated air bubbles flow up from the bottom (Figure A1).

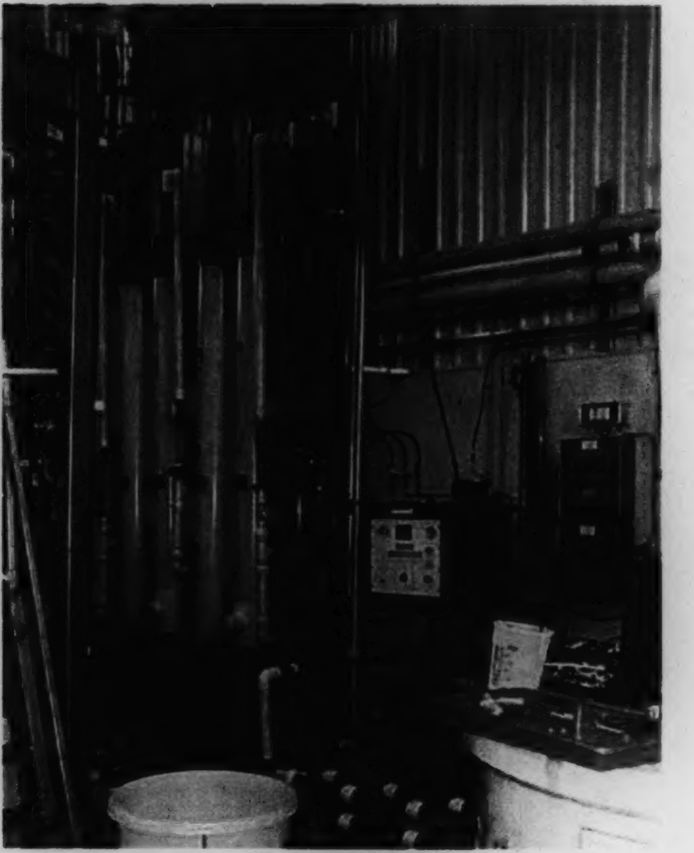


Figure A1 Ozone columns and generator

The water then flows up through the second contactor where it is delivered to a 100 L storage tank before being pumped up to the static mixers and DAF unit on the mezzanine level. Table A1 summarizes data for the ozone columns.

Table A1. Ozone column design and operational data

Sets	3
Columns per set	2
Diameter (mm)	254
Height (mm)	3000
Flow (LPM/column)	33-86
Volume (L/column)	152
Ozone dose (mg/L)	0.00-2.02
Ozone flow (LPM)	0.00-5.75
Contact time (min/column)	1.8-4.6

There are a total of three storage tanks, each with a Grundfos Jet Star Shallow Well Pump (JP-5) with 0.4 kW of power (A2).

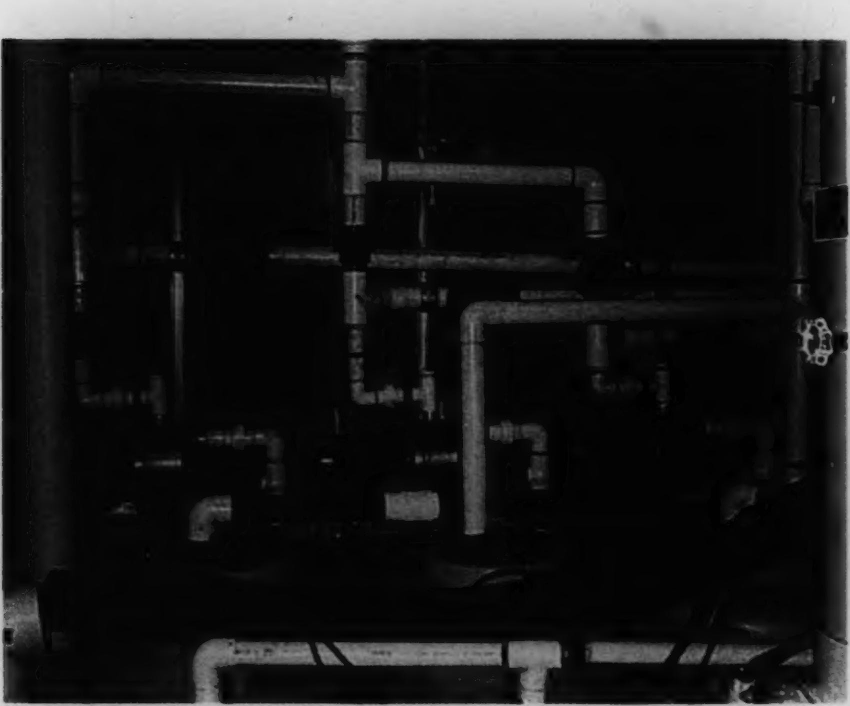


Figure A2 Ozonated water storage tanks and pumps

The volume of each tank is 150 L, which results in a contact time of 1.5 to 2.5 minutes depending on the flow. At maximum efficiency, each pump can deliver approximately

50 LPM to the static mixers on the top floor. A performance chart for the pump is located below in table A2

Table A2 Grundfos Shallow Well JP-5 performance chart

	Discharge pressure (kPa)						
	138	207	241	276	310	345	379
Depth to Water (m)	Capacity (LPM)						
5	49	49	42	34	26	19	11
10	45	45	38	30	23	15	8
15	38	38	38	26	19	11	4
20	30	30	30	23	15	8	
25	23	23	23	19	11	4	

The ozone generator can generate a maximum 1 kg/day of ozone. Ozone is mixed with air at variable flowrates so that ozone can be delivered to the three sets of ozone columns at different doses or flows if necessary. Mounted on the west wall of the pilot plant, next to the ozone generator, is the high concentration ozone dose meter and the low concentration ozone residual meter, both made by PCI, (Figure A3).

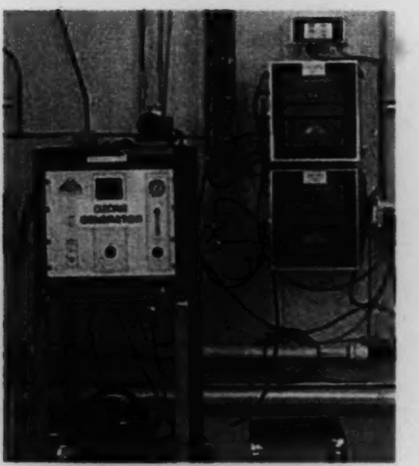


Figure A3 Ozone generator and monitors

The steps for creating ozone and delivering it to the water are as follows:

(1) Be sure that there is cold water being circulated through the ozone generator at all times while it is in operation.

(2) Turn on the compressor located under the ozone generator. The pressure indicated on the generator should be between 1 and 2, and can be adjusted with the knob on the ozone generator.

(3) Flip the power switch on the ozone generator to "ON". The "Percent Ozone" dial governs the amount of ozone created.

(4) Turn on the ozone residual and ozone dose meters. Open the valves located on the left side of the meters to control the flow of gas from the top of the ozone column (where the ozone residual is measured) to the ozone generator. The gas flowrate in each of the meters should be maintained at 1 to 2 LPM. To convert the ozone meter reading to concentration in mg/L, use the following relationships:

HC meter: Ozone dose (mg/L) = meter reading (% by weight) X 11.9
LC meter: Ozone residual (mg/L) = meter reading (ppm) / 843

(5) The ozone dose delivered to the water is calculated as follows:

O_3 dose delivered = (O_3 dose – O_3 residual) X (gas flow rate / water flow rate)

or:

O_3 dose delivered = (O_3 dose) X (gas flow rate) X (0.9 / water flow rate)
Where, 0.9 = 90 percent transfer efficiency

(6) Adjusting the "percent ozone applied" dial on the ozone generator will change the ozone dose delivered. When the gas flow rate is adjusted on the rotameters on the west wall on the left side of the ozone generator, the ozone dose read on the meter will automatically adjust. Therefore, select a constant gas flow rate at the beginning and adjust the percent ozone applied only.

NOTE: The rotameters have two balls in them. The top ball (silver) corresponds to the scale on the left, while the bottom ball (black) corresponds to the scale on the right.

Coagulation

Three 400-liter storage tanks located on the main floor of the pilot plant hold chemicals used in the water treatment process (Figure A4). The chemicals are injected upstream of the static mixers which combine the coagulants with the water. The static mixers are located upstream of the integrated DAF unit. Peristaltic pumps create enough head to transport the chemicals from the storage tanks to the static mixers through plastic tubing.

Figure A4 Coagulant storage tanks and peristaltic pumps

The pumps have a limited flow that they can deliver (approx. 5 to 80 mL/min), therefore it is important to mix the chemicals in the storage tanks at appropriate concentrations. The following are the recipes for the chemicals used in Phase I of the Seymour pilot plant project.

Alum:

$$[Al_2(SO_4)_3] = \%[Al_2(SO_4)_3] \times S_g \times \frac{V_{alum}}{V_{total}}$$

Where,
Concentration of alum mixture in dosing tank (mg/mL) = 60
Concentration of alum mixture form manufacturer (%) = 48
Specific gravity @ 15.6 °C (g/mL) = 1.333
Volume of alum added (L) = 9.9
Total volume of liquid in dosing tank (alum & water, L) = 105

Polyaluminum Chloride (ClearPAC):

$$[PACl] = S_g \times \frac{V_{PACl}}{V_{total}}$$

Where,
Concentration of PACl in dosing tank (mg/mL) = 62
Specific gravity @ 15.6 °C (g/mL) = 1.24
Volume of PACl added (L) = 10
Total volume of liquid in dosing tank (alum & water, L) = 200

Ferric Chloride:

$$[FeCl_3] = \%[FeCl_3] \times S_g \times \frac{V_{Ferric}}{V_{total}}$$

Where,
Concentration of ferric chloride in dosing tank (mg/mL) = 60
Concentration of ferric mixture from manufacturer (%) = 40
Specific gravity @ 15.6 °C (g/mL) = 1.3
Volume of ferric chloride mixture added (L) = 11.5
Total volume in dosing tank (ferric chloride & water, L) = 100

Soda Ash:

$$m_{SodaAsh} = [Na_2CO_3] \times V_{Water}$$

$$V_{SodaAsh} = \frac{m_{SodaAsh}}{S_g}$$

Where,
Mass of soda ash in dosing tank (kg) = 5.0
Concentration of soda ash in dosing tank (mg/mL) = 25
Volume of water in dosing tank (L) = 200
Specific gravity @ 20°C (g/mL) = 0.97
Volume of soda ash added (L) = 5.1

Flocculation

After the rapid mixers, the water is directed to a 2 or 3 stage flocculation basin that is integrated with the DAF flotation tank. 2 or 3 stage flocculation can be accomplished by switching the check valve on the pipe at the inlet to the flocculation tank. Paddle mixer speeds are controlled by dials located in the control panel on the South wall, beside the DAF tank (Figure A5).

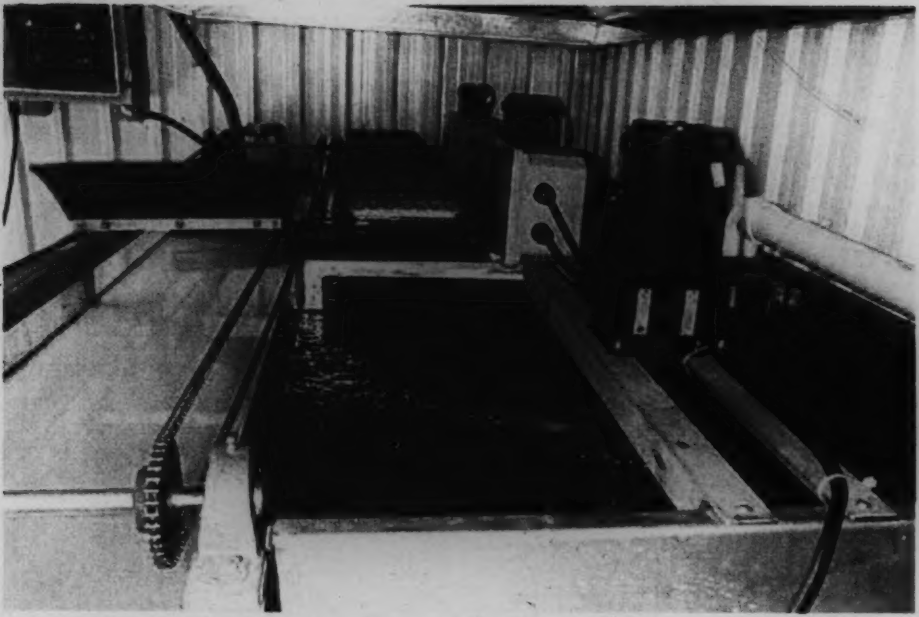


Figure A5 Flocculation basins, DAF tank and control panel

Data on flocculation tank design and operational guidelines is located below in Table A3.

Table A3 Flocculation tank data

Volume per stage (L)	290
Stages	3
Flow (LPM)	60 to 100
Total retention time (min)	8.7 to 14.5
Paddle rotation speed (%)	17 to 40
G (sec^{-1})	27 to 122
Gt	14100 to 105900

DAF Saturator

"Pressurized" dissolved air flotation (DAF) involves supersaturating water with air at several atmospheric pressures, and injecting it through a nozzle into a flotation tank. Recycled water from the flotation tank is mixed with air fed by a pump into the saturator column (Figure A6). The saturator is maintained at a constant pressure by a solenoid valve, which regulates the flow of air into the column. The flow of water into the column will remain approximately constant. The air-water mixture is injected into the flotation tank through a nozzle that can accompany attachments with different opening sizes. The size of the opening determines the backpressure in the saturator as well as the bubble characteristics. Bubbles are produced spontaneously due to the pressure difference across the nozzle. The size of the bubbles, and thus the flotation and bubble attachment characteristics, are also determined by the saturator pressure and injection flow rate.

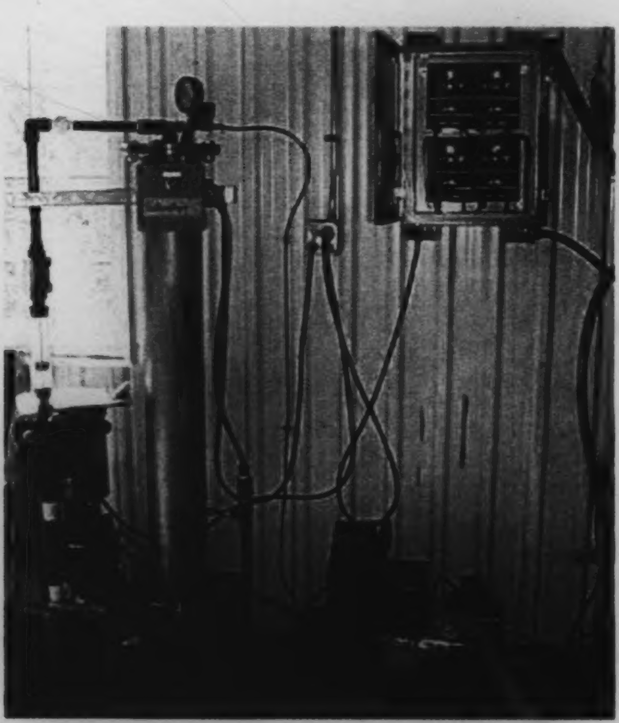


Figure A6 DAF saturator

The saturator is operated as follows:

(1) Turn on the compressor (can be left on continuously). The pressure in the compressor should be maintained at approximately the same pressure that is desired in the saturator (400 to 600 kPa)

(2) Turn on the pump for the recycled water to enter the saturator. The flow should be set so that a recycle ratio of 6 to 12 % can be maintained.

(3) Open the valve at the bottom of the saturator column to allow the flow of the air-water mixture to enter the flotation tank.

(4) Turn control switch to "auto". Turning the switch to "hand" will manually open the solenoid valve to allow a constant flow of air into the saturator. Turning the switch to "off" will close the solenoid valve. When the switch is turned to "auto", the flow of air is regulated by the water column and probes located on the bottom, right side of the saturator. The water level in the column should be maintained at a level of 25 to 50 mm below the bottom of the probes. This can be accomplished by adjusting the flow of water into the saturator column. This may require some "tinkering". As the saturator runs, it will lose pressure, causing the water level in the column to rise. Once the water level rises to a level half way up the probes, the solenoid valve opens to allow air into the saturator. This pressure increase in the saturator will push the water level back down to 25 to 50 mm below the probes. The recycled water flow should remain fairly constant throughout this process.

NOTE: The DAF saturator may take a little while to stabilize.
NOTE: If there is too much water in the saturator, the compressor will get wet. If there is too much air in the saturator, it will violently come out of the saturator nozzle, creating a lot of turbulence in the flotation tank.
NOTE: If the saturator stabilizes and the pressure is too high, but the flow is in an acceptable operating range, replace the nozzle with one that has a larger opening. This will reduce the backpressure, thereby reducing the pressure in the saturator.

Clarification occurs in the flotation tank. The tank is rectangular with clear, polyethylene sides. Two textile scrapers run on a chain along the top of the tank to scrap of the scum and discard it in a waste tank located at the north end of the tank. A dial located in the same control panel as the flocculator paddle controllers controls the paddle speeds. Table A4 summarizes the DAF tank and saturator design criteria.

Table A4 DAF tank and saturator design criteria

DAF tank	
Volume (L)	768.9
Flow (LPM)	60 to 100
Retention time (min)	7.7 to 12.8
Loading rate (m/hr)	5.1 to 8.6
Scraper speed (%)	10 to 15
Saturator	
Saturator pressure (kPa)	320 to 540
Recycle flow (LPM)	6.8 to 14.4
Recycle ratio (%)	8 to 20

Filtration

Three filters follow the DAF unit for the process train being described. The filters operate as constant flow pressure filters, with the flow being automatically adjusted with a flow control valve located near its base. The filters are 152 mm in diameter and approximately 3.5 meters in height (Figure A7). Media is poured into the filters via an access hole at he top of the column. The media can be removed through a similar hole at the filter base.

Figure A7 Filter columns

The filters are controlled using the Simultaneous Control and Data Acquisition (SCADA) system located on the main control computer in the laboratory. The screen, "GVRD Ozone/Filtration Plant Operator Interface", has a pictorial view of the three filters used in the clarification/filtration train. The screen also displays valve layouts and instrumentation readings, (turbidity, headloss). Above the picture of each filter are two buttons labeled "Settings" and "BW Setup" that control the setup and backwashing of the filters. The filters can be run in manual mode or in automatic mode. Backwashes can be performed manually or automatically. Because the backwashes are normally run manually, i.e. controlled by the operator, most of the settings on these two buttons will not be of interest. Filters are normally run in automatic mode, i.e. the flow is maintained at a constant rate by the control system.

To perform a backwash and filter run:

(1) Switch filter from auto mode to manual mode in the BW Setup window, located on the GVRD Ozone/Filtration Plant Operator Interface screen
(2) On the same window, place the backwash valves in the backwash position by pressing the backwash button (the pictorial view of the backwash valves will change from red to green to indicate that they have been opened)
(3) Manually plug in the backwash pump. Do not turn on the on-screen pump (it should remain red)
(4) The filter should now be backwashing. Allow the backwash to run for 5 to 10 minutes, or until the backwash water is clear. Be sure that the clear well does not empty or the pumps will cavitate.
(5) The backwash flow can be manually adjusted by turning the red valve located at the base of each filter. Adjust the valve so that there is maximum bed expansion without spilling media out of the top of the column.
(6) Once the backwash is complete, unplug the pump
(7) Return valves to the filter position
(8) Place filter into automatic mode

Data Acquisition System

On-line data for turbidity, particle, pH, flow, and pressure are delivered to the control computer's database through the PLC (programmable logic controller) and FIX system. These data are continually updated and stored in a database in the C:\FIX 32\HTRData\Seymour\*.h24 directory on the control computer's hard drive. A new file for the data to be placed in is opened automatically every 24 hours. These files can be viewed on the "Historical Display" screen.

The historical display program displays data sets form the on-line instrumentation in an easy-to-view line chart format. Chart configurations have already been set up to display multiple sets of information on the same chart. Charts of interest for the operator are "Raw water CSV", which displays raw water turbidity and particles. Filter 4 CSV, Filter 5 CSV, and Filter 10 CSV display effluent turbidity and particles, as well as flow and pressure for each of the 3 filters. The time period displayed can be changed in the configuration menu. The length of the time period is up to the discretion of the operator, but it should be noted that the number of data points used for creating the chart is independent of the length of the time period displayed.

The data shown on the historical display screen can be saved in an easy to read Microsoft Excel Comma Separated Values (.CSV) file. To save the data in this format, choose an appropriate time period. Irrespective of the length of the time period chosen, the .CSV file will only save approximately 500 lines of data. From the file menu choose export. Save the data with a ".csv" extension in a folder of your choice. It is recommended that data be saved in time blocks corresponding to the length of a filter run (8 to 24 hours).

The entire control system is backed up by an uninteruptable power source (UPS). In the event that the power goes out in the building, the UPS supplies battery power to the control computer for up to two hours. There is also a UPS installed to back up the filter flow control valves, which are automatically controlled by the computer when the filters are in "auto" mode.

System startup and shut down

The main control computer should be left on at all of the time, or it will not read or record data, or control the filters. Startup of the system is performed as follows (the system must be started this way to prevent it from crashing:

(1) Boot system
(2) Close "FIX" window
(3) Open "Intellution FIX" folder
(4) Open "FIX" start-up
(5) Close DDE Client Task
(6) Close UDSERIAL Task
(7) Open UDSERIAL from the Intellution FIX folder
(8) Open DDE Client Task from the Intellution FIX folder.

System shutdown is performed as follows:

(1) Close DDE Client Task
(2) Close UDSERIAL Task
(3) Shutdown FIX window
(4) Turn off control computer

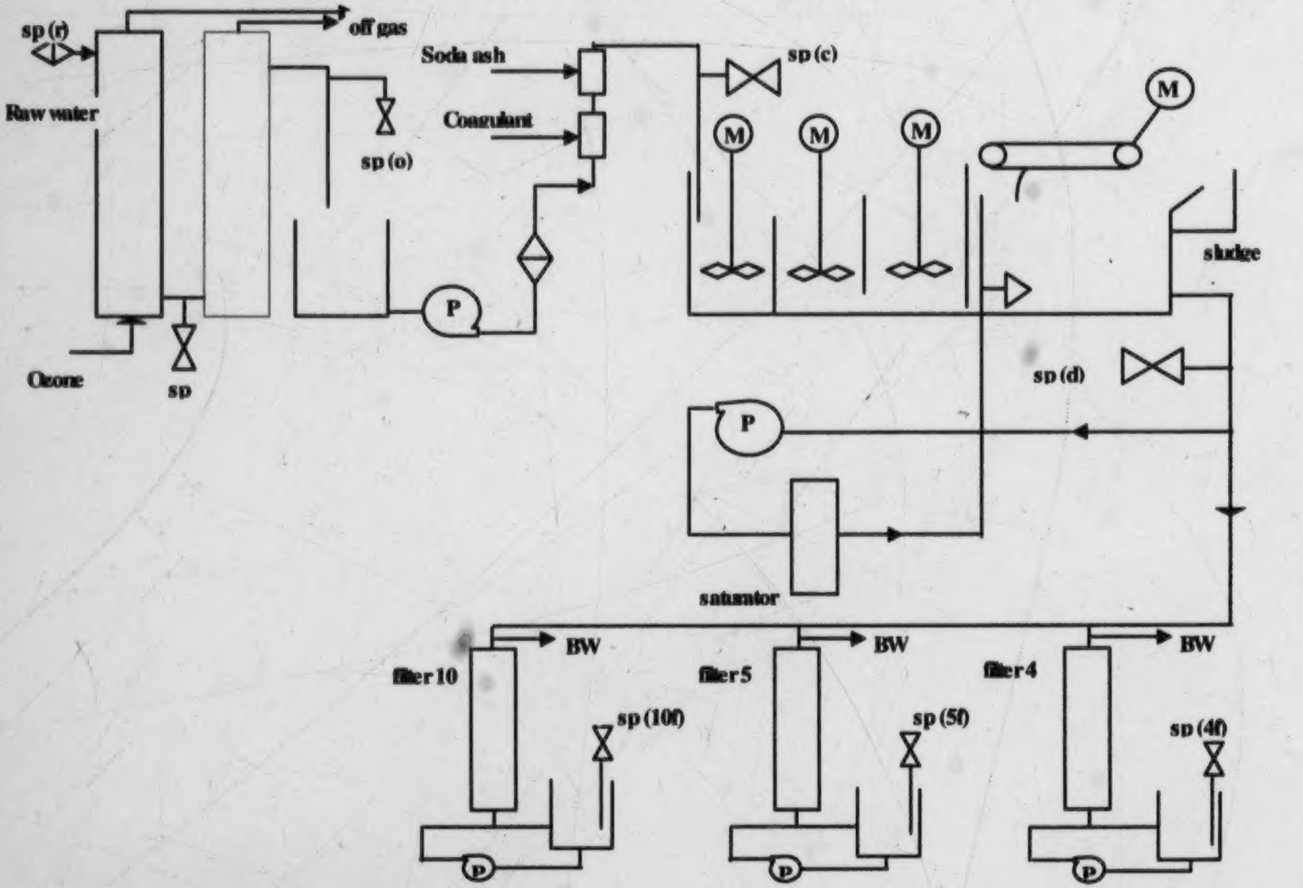
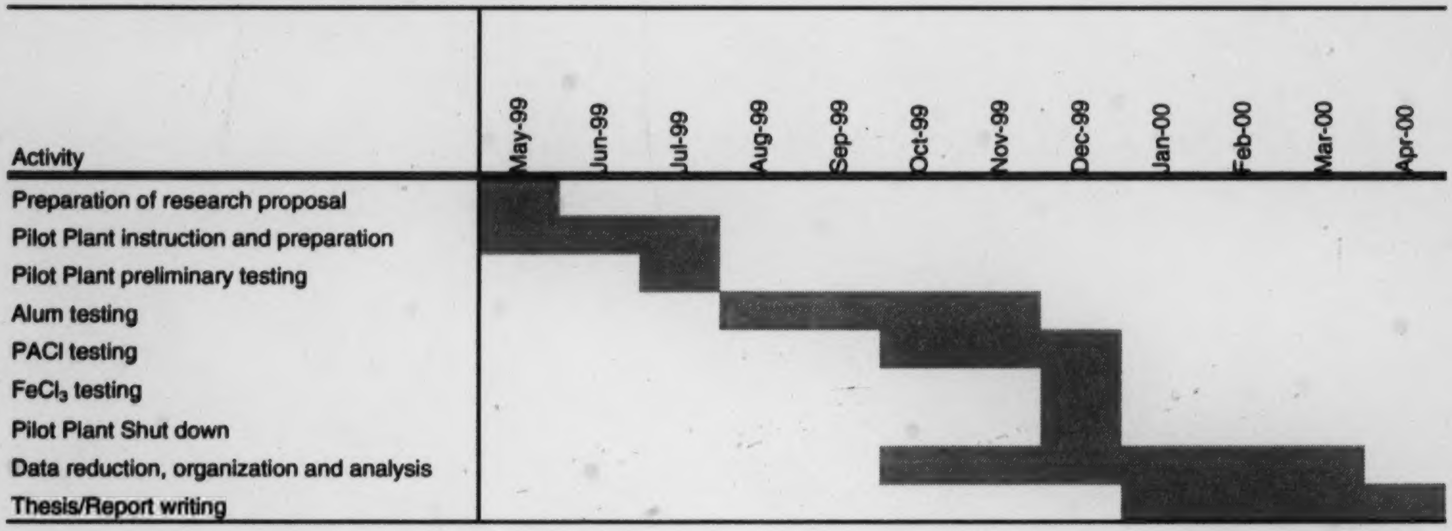

sp (r)
Raw water
Ozone
sp
off gas
sp (o)
P
Soda ash
Coagulant
sp (c)
M
M
M
M
sludge
sp (d)
P
saturator
filter 10
BW
sp (10f)
p
filter 5
BW
sp (5f)
p
filter 4
BW
sp (4f)
p

Figure A8. Pilot plant schematic

Appendix B – Pilot Plant Study Schedule

Table B1 shows the pilot plant study schedule that was performed for the period between May 1999 and April 2000. Preliminary work was performed in May and June. The majority of the pilot testing was done between July and December. Analysis of the data and preparation of the final report was done from January to April 2000.

Table B1 Seymour pilot plant study schedule



Activity	May-99	Jun-99	Jul-99	Aug-99	Sep-99	Oct-99	Nov-99	Dec-99	Jan-00	Feb-00	Mar-00	Apr-00
Preparation of research proposal	■											
Pilot Plant instruction and preparation	■	■	■									
Pilot Plant preliminary testing			■									
Alum testing				■	■	■	■					
PACl testing						■	■	■				
$FeCl_3$ testing								■				
Pilot Plant Shut down								■				
Data reduction, organization and analysis						■	■	■	■	■	■	
Thesis/Report writing									■	■	■	■

Appendix C – Complete Data Tables

Table C1. Raw water summary

	pH	Temp.	Particles						Turbidity	Colour	UV_{254}
Run #		(°C)	>2 µm (#/mL)	>4 µm (#/mL)	>8 µm (#/mL)	>16 µm (#/mL)	>32 µm (#/mL)	>50 µm (#/mL)	(NTU)	(ACU)	(cm^{-1})
0726a	6.4	9.9	468	210	60	0	0	0	0.26	-	-
0727b	6.4	9.2	479	241	75	0	0	0	0.24	-	-
0729c	6.3	9.2	500	244	75	1	0	0	0.27	-	-
0804d	6.3	9.8	436	210	68	0	0	0	0.22	-	-
0805e	6.5	10.1	446	221	80	1	0	0	0.24	-	-
0805f	-	-	-	-	-	-	-	-	-	-	-
0806g	6.4	10.2	-	-	-	-	-	-	0.23	-	-
0809h	6.4	10.3	399	187	62	1	0	0	0.24	-	-
0809i	-	-	-	-	-	-	-	-	-	-	-
0810j	6.6	10.4	384	183	60	0	0	0	0.26	-	-
0810k	-	-	-	-	-	-	-	-	-	-	-
0811l	6.6	10.1	445	210	70	1	0	0	0.23	-	-
0817m	6.6	10.1	379	185	59	1	0	0	0.20	-	-
0817n	-	-	-	-	-	-	-	-	-	-	-
0818o	6.7	10.3	387	187	66	1	0	0	0.21	-	-
0818p	-	-	-	-	-	-	-	-	-	-	-
0819q	6.5	10.8	366	175	79	1	0	0	0.20	-	-
0820r	6.6	10.6	356	173	62	0	0	0	0.21	-	-
0820s	-	-	-	-	-	-	-	-	-	-	-
0821t	-	-	366	194	68	0	0	0	0.21	-	-
0823u	6.7	-	346	182	63	0	0	0	0.20	-	-
0824v	6.7	11	360	191	68	0	0	0	0.20	-	-
0908w	6.6	11.8	1220	545	137	1	0	0	0.59	-	-
0909x	6.6	11.8	1113	482	120	1	0	0	0.55	-	-
0909y	-	-	-	-	-	-	-	-	-	-	-
0910z	-	12.2	912	390	106	1	0	0	0.49	-	-
0912aa	-	11.2	717	311	91	1	0	0	0.43	-	-
0913ab	6.6	12.8	665	297	87	1	0	0	0.40	-	-
0913ac	-	-	-	-	-	-	-	-	-	-	-
0914ad	6.6	12.7	572	266	81	1	0	0	0.37	-	0.07
0914ae	-	-	-	-	-	-	-	-	-	-	-
0915af	6.1	13.1	527	253	81	1	0	0	0.35	-	0.058
0915ag	-	-	-	-	-	-	-	-	-	-	-
0916ah	6.4		468	218	76	1	0	0	0.34	-	0.078
0916ai	-	-	-	-	-	-	-	-	-	-	-
0917aj	6.4	13.2	446	213	74	2	0	0	0.30	-	0.072
0920ak	6.6	13.5	410	199	69	1	0	0	0.31	-	0.039
0920al	-	-	-	-	-	-	-	-	-	-	-
0921am	6.5	13.8	401	190	67	1	0	0	0.32	-	0.081
0921an	-	-	-	-	-	-	-	-	-	-	-
0922ao	6.5	13.7	413	192	66	1	0	0	0.30	-	0.04
0922ap	-	-	-	-	-	-	-	-	-	-	-
0923aq	-	-	392	196	65	1	0	0	0.30	-	0.071
0927ar	6.5	13.2	465	219	80	2	0	0	0.33	-	-
0928as	6.6	13.1	477	232	83	1	0	0	0.33	-	0.052
0928at	-	-	-	-	-	-	-	-	-	-	-
0929au	-	-	-	-	-	-	-	-	-	-	-
1001av	6.5	13	530	261	98	2	0	0	0.32	14	0.056
1001aw	-	-	-	-	-	-	-	-	-	-	-
1002ax	6.4	13	558	275	99	2	0	0	0.34	12	0.06
1004ay	6.4	13	551	286	107	2	0	0	0.31	17	0.062
1004az	-	-	-	-	-	-	-	-	-	-	-
1005ba	6.3	12.9	-	-	-	-	-	-	0.32	14	0.059
1005bb	-	-	-	-	-	-	-	-	-	-	-
1006bc	6.3	13	512	275	103	2	0	0	0.33	21	0.054
1006bd	-	-	-	-	-	-	-	-	-	-	-
1015be	6.5	11	589	293	104	2	0	0	0.35	24	0.07
1015bf	-	-	-	-	-	-	-	-	-	-	-
1016bg	6.4	10.2	645	320	107	1	0	0	0.39	24	0.072
1016bh	-	-	-	-	-	-	-	-	-	-	-
1018bi	6.3	10.8	719	350	116	1	0	0	0.39	23	0.076

Table C1. continued

1018bj	-	-	-	-	-	-	-	-	-	-	-
1019bk	6.4	10.6	771	393	128	1	0	0	0.40	26	0.084
1019bl	-	-	-	-	-	-	-	-	-	-	-
1019bm	-	-	-	-	-	-	-	-	-	-	-
1020bn	-	10.9	731	368	117	1	0	0	0.39	17	0.075
1020bo	-	-	-	-	-	-	-	-	-	-	-
1021bp	6.5	10.2	700	344	116	1	0	0	0.38	19	0.07
1021bq	-	-	-	-	-	-	-	-	-	-	-
1023br	6.4	10.1	734	370	118	1	0	0	0.39	22	0.075
1023bs	-	-	-	-	-	-	-	-	-	-	-
1025bt	6.4	9.9	615	313	102	1	0	0	0.36	19	0.054
1026bu	6.5	9.8	573	293	101	1	0	0	0.37	17	0.071
1028bv	-	-	-	-	-	-	-	-	-	-	-
1029bw	6.4	9.1	1455	766	268	5	0	0	0.66	23	0.078
1029bx	-	-	-	-	-	-	-	-	-	-	-
1103by	6.5	7.9	2040	997	293	4	0	0	0.97	21	0.096
1103bz	-	-	-	-	-	-	-	-	-	-	-
1104ca	6.4	7.2	1922	891	245	1	0	0	0.82	21	0.106
1108cb	6.3	7	5200	2902	983	10	0	0	1.94	27	0.114
1109cc	6.5	6.8	5238	2836	920	5	0	0	1.93	28	0.115
1109cd	-	-	-	-	-	-	-	-	-	-	-
1110ce	6.4	7.1	3596	1823	536	4	0	0	1.44	27	0.117
1110cf	-	-	-	-	-	-	-	-	-	-	-
1111cg	6.3	6.9	3577	1838	563	5	0	0	1.41	26	0.11
1111ch	-	-	-	-	-	-	-	-	-	-	-
1112ci	-	7.2	4035	2147	689	7	0	0	1.70	31	0.119
1115cj	-	7.4	4380	2258	667	3	0	0	1.82	28	0.127
1115ck	-	-	-	-	-	-	-	-	-	-	-
1116cl	6.4	7.5	5126	2636	737	3	0	0	2.29	29	0.115
1117cm	6.3	7.4	5173	2661	761	3	0	0	2.21	28	0.11
1117cn	-	-	-	-	-	-	-	-	-	-	-
1117co	-	-	-	-	-	-	-	-	-	-	-
1117cp	-	-	-	-	-	-	-	-	-	-	-
1117cq	-	-	-	-	-	-	-	-	-	-	-
1118cr	6.5	7.5	4613	2322	636	2	0	0	2.11	28	0.112
1118cs	-	-	-	-	-	-	-	-	-	-	-
1118ct	-	-	-	-	-	-	-	-	-	-	-
1118cu	-	-	-	-	-	-	-	-	-	-	-
1119cv	-	7.1	4262	2084	551	1	0	0	1.88	34	0.108
1123cw	-	6.2	2740	1272	319	1	0	0	1.32	30	0.096
1124cx	6.4	6.1	2803	1317	349	2	0	0	1.25	29	0.095
1124cy	-	-	-	-	-	-	-	-	-	-	-
1124cz	-	-	-	-	-	-	-	-	-	-	-
1124da	-	-	-	-	-	-	-	-	-	-	-
1125db	6.4	6.2	2520	1173	302	1	0	0	1.07	29	0.096
1125dc	-	-	-	-	-	-	-	-	-	-	-
1125dd	-	-	-	-	-	-	-	-	-	-	-
1125de	-	-	-	-	-	-	-	-	-	-	-
1126df	6.3	6	2248	1040	266	1	0	0	0.94	28	0.079
1126dg	-	-	-	-	-	-	-	-	-	-	-
1126dh	-	-	-	-	-	-	-	-	-	-	-
1126di	-	-	-	-	-	-	-	-	-	-	-
1129dj	6.5	6.7	1876	864	234	2	0	0	0.80	28	0.09
1129dk	-	-	-	-	-	-	-	-	-	-	-
1129dl	-	-	-	-	-	-	-	-	-	-	-
1130dm	-	6.5	1579	717	183	0	0	0	0.71	27	0.094
1130dn	-	-	-	-	-	-	-	-	-	-	-
1130do	-	-	-	-	-	-	-	-	-	-	-
1201dp	-	6.4	1535	717	194	2	0	0	0.63	29	0.067
1201dq	-	-	-	-	-	-	-	-	-	-	-
1201dr	-	-	-	-	-	-	-	-	-	-	-
1202ds	6.5	6.2	1309	601	159	1	0	0	0.55	28	0.089
1202dt	-	-	-	-	-	-	-	-	-	-	-
1202du	-	-	-	-	-	-	-	-	-	-	-
1203dv	6.5	5.8	1062	481	128	0	0	0	0.49	31	0.067

Table C1. continued

1204dw	6.6	6	1077	501	144	2	0	0	0.45	33	0.082
1204dx	-	-	-	-	-	-	-	-	-	-	-
1206dy	6.5	5.7	920	423	114	1	0	0	0.42	27	0.087
1206dz	-	-	-	-	-	-	-	-	-	-	-
1207ea	6.5	5.8	874	404	109	1	0	0	0.41	27	0.081
1207eb	-	-	-	-	-	-	-	-	-	-	-
1207ec	-	-	-	-	-	-	-	-	-	-	-
1208ed	-	-	-	-	-	-	-	-	-	-	-
1208ee	6.5	5.2	839	380	106	1	0	0	0.37	30	0.076
1208ef	-	-	-	-	-	-	-	-	-	-	-
1208eg	-	-	-	-	-	-	-	-	-	-	-
1208eh	-	-	-	-	-	-	-	-	-	-	-
1209ei	6.5	5.6	808	369	102	1	0	0	0.37	31	0.071
1209ej	-	-	-	-	-	-	-	-	-	-	-
1210ek	6.5	5.5	727	335	93	1	0	0	0.34	28	0.069
1213el		5	867	449	153	4	0	0	0.37	28	0.068
1214em	6.5	4.4	657	318	103	2	0	0	0.30	25	0.061

Table C2

	Start Time	Ozonation														
		$Q_{influent}$			Q_{ozone}			O_3 output	$Dose_{O3}$	O_3 Residual	$Dose_{applied}$			Contact time, t_c		
		A	B	C	A	B	C				A	B	C	A	B	C
Run #	MM:DD/hh:mm	LPM	LPM	LPM	LPM	LPM	LPM	%	% by weight	ppm	mg/L	mg/L	mg/L	(min)	(min)	(min)
0726a	07:26/14:23	85	-	-	5.7	-	-	70	2.487	0	2.0	-	-	5.3	-	-
0727b	07:27/14:45	85	-	-	5.4	-	-	87.5	2.664	0	2.0	-	-	5.3	-	-
0729c	07:29/10:25	86	-	-	5.5	-	-	100	2.631	800	1.9	-	-	5.3	-	-
0804d	08:04/14:00	85	-	-	2.5	-	-	60	2.677	216	0.9	-	-	5.3	-	-
0805e	08:05/10:10	85	-	-	4.2	-	-	50	1.885	330	1.1	-	-	5.3	-	-
0805f	08:05/15:00	85	-	-	4.2	-	-	50	1.885	330	1.1	-	-	5.3	-	-
0806g	08:06/09:20	85	-	-	4.2	-	-	52	1.900	350	1.1	-	-	5.3	-	-
0809h	08:09/10:20	85	-	-	3.1	-	-	50	2.252	220	1.0	-	-	5.3	-	-
0809i	08:09/16:00	85	-	-		-	-	0	0.000	0	0.0	-	-	5.3	-	-
0810j	08:10/11:20	85	-	-		-	-	0	0.000	0	0.0	-	-	5.3	-	-
0810k	08:10/15:30	85	-	-	4.0	-	-	47.5	1.928	312	1.1	-	-	5.3	-	-
0811l	08:11/09:50	85	-	-		-	-	-	-	-	-	-	-	5.3	-	-
0817m	08:17/10:00	85	-	-	2.6	-	-	28	1.417	195	0.5	-	-	5.3	-	-
0817n	08:17/15:00	85	-	-		-	-	-	-	-	-	-	-	5.3	-	-
0818o	08:18/10:20	85	-	-	2.5	-	-	27.5	1.418	362	0.5	-	-	5.3	-	-
0818p	08:18/15:50	85	-	-	2.5	-	-	27.5	1.408	268	0.5	-	-	5.3	-	-
0819q	08:19/11:45	85	-	-	3.1	-	-	61	2.380	423	1.0	-	-	5.3	-	-
0820r	08:20/11:05	85	-	-		-	-	-	-	-	-	-	-	5.3	-	-
0820s	08:20/15:10	85	-	-	5.2	-	-	94	2.616	521	1.9	-	-	5.3	-	-
0821t	08:21/13:45	85	-	-	4.2	-	-	50	1.823	342	1.0	-	-	5.3	-	-
0823u	08:23/14:45	85	-	-	2.5	-	-	26	1.373	235	0.5	-	-	5.3	-	-
0824v	08:24/11:35	85	-	-		-	-	-	-	-	-	-	-	5.3	-	-
0908w	09:08/11:45	85	-	-	2.3	-	-	32	1.580	941	0.5	-	-	5.3	-	-
0909x	09:09/11:40	85	-	-	3.4	-	-	26	1.323	200	0.6	-	-	5.3	-	-
0909y	09:09/13:55	85	-	-	3.5	-	-	51	1.923	323	0.9	-	-	5.3	-	-
0910z	09:10/11:55	85	-	-		-	-	-	-	-	-	-	-	5.3	-	-
0912aa	09:12/13:50	85	-	-	3.6	-	-	38	1.540	-	0.7	-	-	5.3	-	-
0913ab	09:13/12:15	85	-	-		-	-	-	-	-	-	-	-	5.3	-	-
0913ac	09:13/15:35	85	-	-	4.1	-	-	25	0.947	-	0.5	-	-	5.3	-	-
0914ad	09:14/09:45	85	-	-	4.1	-	-	50	2.318	-	1.2	-	-	5.3	-	-
0914ae	09:14/15:40	65	49	-	4.3	3.1	-	43	1.532	-	1.1	1.0	-	7.0	9.3	-
0915af	09:15/10:55	65	49	-			-	-	-	-	-	-	-	7.0	9.3	-
0915ag	09:15/15:25	65	49	-			-	-	-	-	-	-	-	7.0	9.3	-
0916ah	09:16/11:50	55	49	-	2.3	1.8	-	24	1.302	-	0.6	0.5	-	8.3	9.3	-
0916ai	09:16/15:35	55	49	-	1.8	1.4	-	13	0.750	-	0.3	0.2	-	8.3	9.3	-
0917aj	09:17/10:05	55	49	-	1.7	1.3	-	13	0.876	-	0.3	0.2	-	8.3	9.3	-
0920ak	09:20/09:55	55	47	-	1.5	1.3	-	12	0.926	-	0.3	0.3	-	8.3	9.7	-
0920al	09:20/16:10	55	49	-	1.5	1.3	-	11	0.921	-	0.3	0.3	-	8.3	9.3	-
0921am	09:21/11:00	55	49	-	1.5	1.3	-	11	0.921	-	0.3	0.3	-	8.3	9.3	-
0921an	09:21/15:15	55	49	-	1.5	1.3	-	11	0.921	-	0.3	0.3	-	8.3	9.3	-
0922ao	09:22/11:45	55	49	-	1.5	1.3	-	11	0.918	-	0.3	0.3	-	8.3	9.3	-
0922ap	09:22/15:38	55	49	-	1.5	1.2	-	11	0.921	-	0.3	0.2	-	8.3	9.3	-
0923aq	09:23/10:45	55	47	-	1.5	1.3	-	25	1.853	-	0.5	0.5	-	8.3	9.7	-
0927ar	09:27/14:30	55	48	-			-	-	-	-	-	-	-	8.3	9.5	-
0928as	09:28/10:30	53	47	-	1.5	1.2	-	25	1.910	-	0.6	0.5	-	8.6	9.7	-
0928at	09:28/13:03	54	47	-	1.5	1.3	-	25	1.910	-	0.5	0.5	-	8.4	9.7	-
0929au	09:29/15:15	54	47	-			-	-	-	-	-	-	-	8.4	9.7	-
1001av	10:01/09:55	55	39	-			-	-	-	-	-	-	-	8.3	11.6	-
1001aw	10:01/14:05	55	39	-			-	-	-	-	-	-	-	8.3	11.6	-
1002ax	10:02/13:50	54	38	-	1.4	1.1	-	11	1.028	-	0.3	0.3	-	8.4	11.9	-
1004ay	10:04/10:15	52	38	-	1.5	1.2	-	22	1.780	-	0.5	0.6	-	8.7	11.9	-
1004az	10:04/15:55	52	38	-	1.5	1.2	-	23	1.793	-	0.5	0.6	-	8.7	11.9	-
1005ba	10:05/11:07	54	36	-	1.4	1.0	-	11	0.943	-	0.3	0.3	-	8.4	12.6	-
1005bb	10:05/13:55	54	36	-	1.5	1.1	-	11	0.888	-	0.3	0.3	-	8.4	12.6	-
1006bc	10:06/09:40	53	33	-	1.5	1.0	-	11	0.893	-	0.3	0.3	-	8.6	13.8	-
1006bd	10:06/14:10	53	33	-	1.5	1.0	-	22	1.712	-	0.5	0.6	-	8.6	13.8	-
1015be	10:15/11:05	60	44.5	-	1.5	1.3	-	12	0.942	-	0.3	0.3	-	7.6	10.2	-
1015bf	10:15/15:20	60	44.5	-			-	-	-	-	-	-	-	7.6	10.2	-
1016bg	10:16/11:07	60	44.5	-			-	-	-	-	-	-	-	7.6	10.2	-
1016bh	10:16/14:15	60	44.5	-	1.5	1.3	-	11	0.906	-	0.2	0.3	-	7.6	10.2	-
1018bi	10:18/11:10	60	44.5	-			-	-	-	-	-	-	-	7.6	10.2	-
1018bj	10:18/15:50	60	44.5	-	1.4	1.2	-	11	0.957	-	0.2	0.3	-	7.6	10.2	-
1019bk	10:19/10:25	60	43.5	-			-	-	-	-	-	-	-	7.6	10.4	-
1019bl	10:19/13:55	60	44.5	-			-	-	-	-	-	-	-	7.6	10.2	-
1019bm	10:19/16:40	59	44.5	-			-	-	-	-	-	-	-	7.7	10.2	-
1020bn	10:20/09:15	60	42	-			-	-	-	-	-	-	-	7.6	10.8	-
1020bo	10:20/15:50	60	42	-	1.4	1.2	-	11	0.903	-	0.2	0.3	-	7.6	10.8	-
1021bp	10:21/10:30	59	43	-	1.5	1.2	-	26	1.873	-	0.5	0.5	-	7.7	10.6	-
1021bq	10:21/14:40	59	43	-	1.5	1.2	-	10	0.941	-	0.2	0.3	-	7.7	10.6	-
1023br	10:23/13:35	57	43	-	1.4	1.2	-	10	0.918	-	0.2	0.3	-	8.0	10.6	-
1023bs	10:23/16:00	57	43	-	1.4	1.2	-	10	0.918	-	0.2	0.3	-	8.0	10.6	-
1025bt	10:25/11:30	58	41	-	1.5	1.2	-	25	low lamp	-	?	?	-	8.1	11.1	-
1028bu	10:28/10:10	59	44	-			-	-	-	-	-	-	-	7.7	10.3	-
1028bv	10:28/13:35	63	46	-	1.3	1.2	-	25	-	-	-	-	-	7.2	9.9	-
1029bw	10:29/10:00	68	50	-	1.5	1.2	-	50	-	-	-	-	-	6.7	9.1	-
1029bx	10:29/13:20	67	50	-	1.5	1.2	-	-	-	-	-	-	-	6.8	9.1	-
1103by	11:03/09:50	57	40	-			-	-	-	-	-	-	-	8.0	11.4	-
1103bz	11:03/13:15	57	40	-			-	-	-	-	-	-	-	8.0	11.4	-
1104ca	11:04/11:10	64	45	-			-	-	-	-	-	-	-	7.1	10.1	-
1108cb	11:08/11:50	68	47	-			-	-	-	-	-	-	-	6.7	9.7	-
1109cc	11:09/09:45	66	45	-			-	-	-	-	-	-	-	6.9	10.1	-
1109cd	11:09/13:05	66	45	-	1.6	1.3	-	20	-	-	-	-	-	6.9	10.1	-
1110ce	11:10/09:20	68	48	-			-	-	-	-	-	-	-	6.7	9.5	-
1110cf	11:10/12:30	68	48	-			-	-	-	-	-	-	-	6.7	9.5	-

Contact time, t_c		Coagulation				Flocculation						DAF					
B	C	Type	Dose	Soda Ash	PAC dose	Flow$_{influent}$	Stages	V$_{paddle}$	G	Detention time, t_f	Gt	Q$_{recycle}$	R.R.	P$_{sat}$	V$_{saturator}$	dL/dt	Detention time, t_d
(min)	(min)		mg/L	amg/L	mg/L	LPM	#	%	s^{-1}	(min)		LPM	%	kPa	%	m/hr	(min)
-	-	none	0	no	0	80	3	20	30	10.9	19575	14.4	18.0	420	10	6.9	9.6
-	-	none	0	no	0	80	3	20	30	10.9	19575	14.4	18.0	420	10	6.9	9.6
-	-	alum	10	no	0	80	3	20	30	10.9	19575	8.7	10.9	460	10	6.9	9.6
-	-	alum	8	9	0	80	3	20	30	10.9	19575	8.3	10.4	380	10	6.9	9.6
-	-	alum	8	9	0	80	3	20	30	10.9	19575	9.5	11.9	440	10	6.9	9.6
-	-	alum	4	yes	0	80	3	20	30	10.9	19575	9.5	11.9	440	10	6.9	9.6
-	-	alum	4	yes	0	80	3	20	30	10.9	19575	9.5	11.9	440	10	6.9	9.6
-	-	alum	8	7.5	0	80	3	20	30	10.9	19575	9.1	11.4	410	10	6.9	9.6
-	-	alum	8	yes	0	80	3	20	30	10.9	19575	9.1	11.4	410	10	6.9	9.6
-	-	alum	4	yes	0	80	3	20	30	10.9	19575	9.1	11.4	410	10	6.9	9.6
-	-	alum	4	yes	0	80	3	20	30	10.9	19575	9.8	12.3	420	10	6.9	9.6
-	-	alum	8	yes	0	80	3	20	30	10.9	19575	9.8	12.3	430	10	6.9	9.6
-	-	alum	6	yes	0	80	3	20	30	10.9	19575	9.8	12.3	430	10	6.9	9.6
-	-	alum	6	yes	0	80	3	20	30	10.9	19575	9.8	12.3	430	10	6.9	9.6
-	-	alum	8	yes	0	80	3	20	30	10.9	19575	9.8	12.3	440	10	6.9	9.6
-	-	alum	10	yes	0	80	3	20	30	10.9	19575	9.8	12.3	450	10	6.9	9.6
-	-	alum	10	yes	0	80	3	20	30	10.9	19575	9.8	12.3	450	10	6.9	9.6
-	-	alum	10	yes	0	80	3	20	30	10.9	19575	9.8	12.3	440	10	6.9	9.6
-	-	none	-	yes	0	80	3	20	30	10.9	19575	9.8	12.3	440	10	6.9	9.6
-	-	none	-	yes	0	80	3	20	30	10.9	19575	9.8	12.3	440	10	6.9	9.6
-	-	none	-	yes	0	80	3	20	30	10.9	19575	9.8	12.3	440	10	6.9	9.6
-	-	none	-	no	0	80	3	20	30	10.9	19575	9.8	12.3	440	10	6.9	9.6
-	-	alum	8	yes	0	80	3	20	30	10.9	19575	9.5	11.9	400	10	6.9	9.6
-	-	alum	10	yes	0	80	3	20	30	10.9	19575	9.1	11.4	400	10	6.9	9.6
-	-	alum	10	yes	0	80	3	20	30	10.9	19575	9.1	11.4	390	10	6.9	9.6
-	-	alum	10	no	0	80	3	20	30	10.9	19575	9.5	11.9	390	10	6.9	9.6
-	-	alum	10	no	0	80	3	20	30	10.9	19575	9.8	12.3	440	10	6.9	9.6
-	-	alum	4	no	0	80	3	20	30	10.9	19575	10.0	12.5	360	10	6.9	9.6
-	-	alum	4	no	0	80	3	20	30	10.9	19575	10.6	13.3	400	10	6.9	9.6
-	-	alum	4	no	0	80	3	20	30	10.9	19575	11.4	14.3	410	10	6.9	9.6
9.3	-	alum	10	yes	0	100	3	20	30	8.7	15660	9.8	9.8	440	10	8.6	7.7
9.3	-	alum	10	yes	0	100	3	20	30	8.7	15660	10.6	10.6	340	10	8.6	7.7
9.3	-	alum	4	yes	0	100	3	20	30	8.7	15660	10.6	10.6	360	10	8.6	7.7
9.3	-	alum	4	yes	0	100	3	20	30	8.7	15660	9.8	9.8	340	10	8.6	7.7
9.3	-	alum	7	yes	0	90	3	20	30	9.7	17400	9.8	10.9	340	10	7.7	8.5
9.3	-	alum	7	yes	0	100	2	20	30	8.7	15660	9.8	9.8	340	10	8.6	7.7
9.7	-	alum	7	yes	0	100	3	35	100	8.7	52200	10.6	10.6	320	10	8.6	7.7
9.3	-	alum	7	yes	0	100	2	35	100	8.7	52200	10.6	10.6	320	10	8.6	7.7
9.3	-	alum	7	yes	0	80	2	35	100	10.9	65250	9.8	12.3	360	10	6.9	9.5
9.3	-	alum	7	yes	0	80	3	35	100	10.9	65250	9.8	12.3	360	10	6.9	9.6
9.3	-	alum	7	yes	0	80	2	20	30	10.9	19575	9.1	11.4	460	10	6.9	9.6
9.3	-	alum	7	yes	0	100	3	28	63	8.7	32886	9.1	9.1	460	10	8.6	7.7
9.7	-	alum	7	yes	0	100	3	28	63	8.7	32886	9.1	9.1	460	10	8.6	7.7
9.5	-	PACl	10	yes	0	100	3	25	51	8.7	26622	8.7	8.7	420	10	8.6	7.7
9.7	-	PACl	10	yes	0	98	3	25	51	8.9	27165	9.1	9.3	410	10	8.4	7.8
9.7	-	PACl	4	yes	0	99	3	25	51	8.8	26891	9.1	9.2	405	10	8.5	7.8
9.7	-	PACl	4	yes	0	99	3	25	51	8.8	26891	8.7	8.8	540	10	8.5	7.8
11.6	-	PACl	10	yes	0	70	3	25	51	12.4	38031	6.8	9.7	540	10	6.0	11.0
11.6	-	PACl	4	yes	0	70	3	25	51	12.4	38031	7.6	10.9	420	10	6.0	11.0
11.9	-	PACl	10	yes	0	70	3	25	51	12.4	38031	7.9	11.3	440	10	6.0	11.0
11.9	-	PACl	10	yes	0	70	3	25	51	12.4	38031	7.9	11.3	420	10	6.0	11.0
11.9	-	PACl	4	yes	0	70	3	25	51	12.4	38031	8.3	11.9	420	10	6.0	11.0
12.6	-	PACl	15	yes	0	70	3	25	51	12.4	38031	8.3	11.9	400	10	6.0	11.0
12.6	-	PACl	10	no	0	70	3	25	51	12.4	38031	7.9	11.3	420	10	6.0	11.0
13.8	-	PACl	10	yes	0	70	3	25	51	12.4	38031	7.9	11.3	420	10	6.0	11.0
13.8	-	PACl	15	yes	0	70	3	25	51	12.4	38031	7.9	11.3	420	10	6.0	11.0
10.2	-	PACl	7	4.5	0	85	3	25	51	10.2	31320	8.3	9.8	420	10	7.3	9.0
10.2	-	PACl	7	4.5	0	85	3	25	51	10.2	31320	8.3	9.8	420	10	7.3	9.0
10.2	-	PACl	15	yes	0	90	3	25	51	9.7	29580	8.3	9.2	420	10	7.7	8.5
10.2	-	PACl	10	4	0	90	3	25	51	9.7	29580	8.3	9.2	480	10	7.7	8.5
10.2	-	PACl	10	yes	-	90	3	25	51	9.7	29580	9.1	10.1	440	10	7.7	8.5
10.2	-	PACl	15	yes	0	90	3	25	51	9.7	29580	8.7	9.7	420	15	7.7	8.5
10.4	-	PACl	10	3	0	90	3	25	51	9.7	29580	8.3	9.2	380	15	7.7	8.5
10.2	-	alum	10	6	0	90	3	25	51	9.7	29580	8.7	9.7	420	15	7.7	8.5
10.2	-	alum	4	3	0	91	3	25	51	9.6	29255	8.3	9.1	410	15	7.8	8.4
10.8	-	alum	15	yes	0	90	3	25	51	9.7	29580	9.1	10.1	380	15	7.7	8.5
10.8	-	alum	10	5.5	0	90	3	25	51	9.7	29580	8.7	9.7	410	15	7.7	8.5
10.6	-	alum	10	5.5	0	90	3	25	51	9.7	29580	8.7	9.7	420	15	7.7	8.5
10.6	-	alum	4	3	0	90	3	25	51	9.7	29580	8.7	9.7	420	15	7.7	8.5
10.6	-	alum	15	3	0	90	3	25	51	9.7	29580	9.1	10.1	390	15	7.7	8.5
10.6	-	alum	7	3	0	90	3	25	51	9.7	29580	9.1	10.1	390	15	7.7	8.5
11.1	-	alum	4	3	0	90	3	25	51	9.7	29580	9.8	10.9	390	15	7.7	8.5
10.3	-	alum	7	3	0	90	3	25	51	9.7	29580	9.8	10.9	380	15	7.7	8.5
9.9	-	alum	7	3	0	90	3	25	51	9.7	29580	10.6	11.8	380	15	7.7	8.5
9.1	-	alum	7	4	0	100	3	25	51	8.7	26622	10.6	10.6	380	15	8.6	7.7
9.1	-	alum	15	4	0	100	3	25	51	8.7	26622	10.6	10.6	380	15	8.6	7.7
11.4	-	alum	7	no	5	80	3	25	51	10.9	33278	8.3	10.4	520	15	6.9	9.6
11.4	-	alum	7	no	10	80	3	25	51	10.9	33278	8.3	10.4	520	15	6.9	9.6
10.1	-	alum	7	no	14	80	3	25	51	10.9	33278	8.3	10.4	500	15	6.9	9.6
9.7	-	alum	7	3	0	100	3	25	51	8.7	26622	8.3	8.3	490	15	8.6	7.7
10.1	-	alum	10	3	0	100	3	25	51	8.7	26622	8.3	8.3	490	15	8.6	7.7
10.1	-	alum	10	3	0	100	3	25	51	8.7	26622	8.3	8.3	490	15	8.6	7.7
9.5	-	alum	10	yes	0	100	3	25	51	8.7	26622	9.1	9.1	460	15	8.6	7.7
9.5	-	alum	15	4	0	100	3	25	51	8.7	26622	9.1	9.1	440	15	8.6	7.7

Table C2 cont.

1111cg	11:11/09:35	67	47	-			-	-	-	-	-	-	-	6.8	9.7	-	alum
1111ch	11:11/12:30	67	47	-			-	-	-	-	-	-	-	6.8	9.7	-	alum
1112ci	11:12/10:30	68	47	-	1.3	1.1	-	25	-	-	-	-	-	6.7	9.7	-	alum
1115cj	11:15/09:50	65	45	-	1.6	1.3	-	15	-	-	-	-	-	7.0	10.1	-	alum
1115ck	11:15/13:20	65	45	-	1.6	1.3	-	15	-	-	-	-	-	7.0	10.1	-	alum
1116cl	11:16/12:35	65	45	-	1.6	1.3	-	13	-	-	-	-	-	7.0	10.1	-	alum
1117cm	11:17/09:40	65	45	-	0.0	0.0	-	-	-	-	-	-	-	7.0	10.1	-	alum
1117cn	11:17/11:30	65	45	-	0.0	0.0	-	-	-	-	-	-	-	7.0	10.1	-	alum
1117co	11:17/13:15	65	45	-	0.0	0.0	-	-	-	-	-	-	-	7.0	10.1	-	alum
1117cp	11:17/14:25	65	45	-	0.0	0.0	-	-	-	-	-	-	-	7.0	10.1	-	alum
1117cq	11:17/15:35	65	45	-	0.0	0.0	-	-	-	-	-	-	-	7.0	10.1	-	alum
1118cr	11:18/09:25	65	45	-	0.0	0.0	-	-	-	-	-	-	-	7.0	10.1	-	alum
1118cs	11:18/10:45	65	45	-	0.0	0.0	-	-	-	-	-	-	-	7.0	10.1	-	alum
1118ct	11:18/12:15	65	45	-	0.0	0.0	-	-	-	-	-	-	-	7.0	10.1	-	alum
1118cu	11:18/13:40	65	45	-	0.0	0.0	-	-	-	-	-	-	-	7.0	10.1	-	alum
1119cv	11:19/10:00	65	46	-	0.0	0.0	-	-	-	-	-	-	-	7.0	9.9	-	PACl
1123cw	11:23/09:05	66	46	-	0.0	0.0	-	-	-	-	-	-	-	6.9	9.9	-	PACl
1124cx	11:24/09:15	65	45	-	0.0	0.0	-	-	-	-	-	-	-	7.0	10.1	-	PACl
1124cy	11:24/10:35	65	45	-	0.0	0.0	-	-	-	-	-	-	-	7.0	10.1	-	PACl
1124cz	11:24/12:20	65	45	-	0.0	0.0	-	-	-	-	-	-	-	7.0	10.1	-	PACl
1124da	11:24/13:50	65	45	-	0.0	0.0	-	-	-	-	-	-	-	7.0	10.1	-	PACl
1125db	11:25/09:45	65	46	-	1.4	1.1	-	13	1.120	-	0.2	0.3	-	7.0	9.9	-	PACl
1125dc	11:25/11:40	65	46	-	1.4	1.1	-	63	3.296	-	0.7	0.8	-	7.0	9.9	-	PACl
1125dd	11:25/13:20	65	46	-	1.4	1.1	-	60	3.242	-	0.7	0.8	-	7.0	9.9	-	PACl
1125de	11:25/15:25	65	45	-	0.0	0.0	-	-	-	-	-	-	-	7.0	10.1	-	PACl
1126df	11:26/10:10	65	45	-	1.4	1.1	-	14	1.143	-	0.3	0.3	-	7.0	10.1	-	PACl
1126dg	11:26/12:20	65	45	-	1.4	1.1	-	14	1.178	-	0.3	0.3	-	7.0	10.1	-	PACl
1126dh	11:26/13:45	65	45	-	1.4	1.1	-	63	3.362	-	0.7	0.8	-	7.0	10.1	-	PACl
1126di	11:26/15:40	65	45	-	1.4	1.1	-	-	1.093	-	0.2	0.3	-	7.0	10.1	-	PACl
1129dj	11:29/09:08	64	45	-	1.4	1.1	-	13	1.075	-	0.2	0.3	-	7.1	10.1	-	PACl
1129dk	11:29/11:15	65	45	-	1.4	1.1	-	13	1.075	-	0.2	0.3	-	7.0	10.1	-	PACl
1129dl	11:29/13:45	64	45	-	1.4	1.1	-	65	3.273	-	0.7	0.8	-	7.1	10.1	-	PACl
1130dm	11:30/10:00	66	46	-	1.3	1.1	-	60	3.205	-	0.7	0.8	-	6.9	9.9	-	PACl
1130dn	11:30/12:05	66	46	-	1.3	1.1	-	17	1.142	-	0.2	0.3	-	6.9	9.9	-	PACl
1130do	11:30/14:30	66	46	-	0.0	0.0	-	-	-	-	-	-	-	6.9	9.9	-	PACl
1201dp	12:01/10:05	65	45	-	1.4	1.1	-	14	1.167	-	0.3	0.3	-	7.0	10.1	-	PACl
1201dq	12:01/12:35	65	45	-	0.0	0.0	-	-	-	-	-	-	-	7.0	10.1	-	PACl
1201dr	12:01/13:45	65	45	-	1.4	1.1	-	59	3.185	-	0.7	0.8	-	7.0	10.1	-	PACl
1202ds	12:02/10:00	66	46	-	0.0	0.0	-	-	-	-	-	-	-	6.9	9.9	-	FeCl3
1202dt	12:02/11:50	66	46	-	0.0	0.0	-	-	-	-	-	-	-	6.9	9.9	-	FeCl3
1202du	12:02/14:50	66	46	-	0.0	0.0	-	-	-	-	-	-	-	6.9	9.9	-	FeCl3
1203dv	12:03/09:25	65	46	-	0.0	0.0	-	-	-	-	-	-	-	7.0	9.9	-	FeCl3
1204dw	12:04/10:30	64	45	-	0.0	0.0	-	-	-	-	-	-	-	7.1	10.1	-	FeCl3
1204dx	12:04/14:00	64	45	-	0.0	0.0	-	-	-	-	-	-	-	7.1	10.1	-	FeCl3
1206dy	12:06/10:10	65	46	-	1.3	1.1	-	15	1.201	-	0.3	0.3	-	7.0	9.9	-	FeCl3
1206dz	12:06/14:00	65	46	-	1.3	1.1	-	65	3.325	-	0.7	0.8	-	7.0	9.9	-	FeCl3
1207ea	12:07/10:45	65	45	-	0.0	0.0	-	-	-	-	-	-	-	7.0	10.1	-	FeCl3
1207eb	12:07/13:15	65	45	-	1.4	1.1	-	18	1.267	-	0.3	0.3	-	7.0	10.1	-	FeCl3
1207ec	12:07/15:00	65	45	-	1.4	1.1	-	65	3.330	-	0.7	0.8	-	7.0	10.1	-	FeCl3
1208ed	12:08/09:20	65	45	-	0.0	0.0	-	-	-	-	-	-	-	7.0	10.1	-	FeCl3
1208ee	12:08/10:50	65	45	-	1.4	1.1	-	15	1.217	-	0.3	0.3	-	7.0	10.1	-	FeCl3
1208ef	12:08/13:00	65	45	-	1.4	1.1	-	15	1.225	-	0.3	0.3	-	7.0	10.1	-	FeCl3
1208eg	12:08/14:30	65	45	-	1.4	1.1	-	15	1.253	-	0.3	0.3	-	7.0	10.1	-	FeCl3
1208eh	12:08/15:50	65	45	-	1.4	1.1	-	15	1.245	-	0.3	0.3	-	7.0	10.1	-	FeCl3
1209ei	12:09/10:00	65	45	-	1.3	1.1	-	15	1.236	-	0.3	0.3	-	7.0	10.1	-	FeCl3
1209ej	12:09/13:00	65	45	-	0.0	0.0	-	-	-	-	-	-	-	7.0	10.1	-	FeCl3
1210ek	12:10/10:25	65	45	-	1.3	1.1	-	15	1.298	-	0.3	0.3	-	7.0	10.1	-	FeCl3
1213el	12:13/09:48	65	45	-	0.0	0.0	-	-	-	-	-	-	-	7.0	10.1	-	FeCl3
1214em	12:14/11:00	65	45	-	1.4	1.1	-	15	1.318	-	0.3	0.3	-	7.0	10.1	-	FeCl3

6.8	9.7	-	alum	10	10	0	100	3	25	51	8.7	26622	8.7	8.7	440	15	8.6	7.7
6.8	9.7	-	alum	10	no	0	100	3	25	51	8.7	26622	9.5	9.5	440	15	8.6	7.7
6.7	9.7	-	alum	10	no	0	100	3	25	51	8.7	26622	9.5	9.5	440	15	8.6	7.7
7.0	10.1	-	alum	10	4	0	100	3	17	27	8.7	14094	9.5	9.5	430	15	8.6	7.7
7.0	10.1	-	alum	10	4	0	100	3	40	122	8.7	63684	9.5	9.5	430	15	8.6	7.7
7.0	10.1	-	alum	12	4	0	100	2	20	31	8.7	16182	9.8	9.8	460	15	8.6	7.7
7.0	10.1	-	alum	10	no	0	80	3	20	31	10.9	20228	9.8	12.3	460	15	6.9	9.6
7.0	10.1	-	alum	11	no	0	100	2	20	31	8.7	16182	9.8	9.8	460	15	8.6	7.7
7.0	10.1	-	alum	12	no	0	60	3	20	31	14.5	26970	9.8	16.3	460	15	5.1	12.8
7.0	10.1	-	alum	13	no	0	60	3	32	80	14.5	69600	9.8	16.3	460	15	5.1	12.8
7.0	10.1	-	alum	14	no	0	60	3	40	122	14.5	106140	9.8	16.3	460	15	5.1	12.8
7.0	10.1	-	alum	15	no	0	100	2	32	80	8.7	41760	9.8	9.8	460	15	8.6	7.7
7.0	10.1	-	alum	16	no	0	100	2	40	122	8.7	63684	9.8	9.8	460	15	8.6	7.7
7.0	10.1	-	alum	17	no	0	80	3	32	80	10.9	52200	9.8	12.3	460	15	6.9	9.6
7.0	10.1	-	alum	18	no	0	80	3	40	122	10.9	79005	9.8	12.3	460	15	6.9	9.6
7.0	9.9	-	PACl	10	no	0	60	3	20	30	14.5	26100	9.8	16.3	440	15	5.1	12.8
6.9	9.9	-	PACl	12	yes	0	60	3	20	30	14.5	26100	9.8	16.3	370	15	5.1	12.8
7.0	10.1	-	PACl	20	5	0	60	3	22	36	14.5	31320	9.8	16.3	500	15	5.1	12.8
7.0	10.1	-	PACl	30	5	0	60	3	22	36	14.5	31320	9.8	16.3	500	15	5.1	12.8
7.0	10.1	-	PACl	40	5	0	60	3	22	36	14.5	31320	9.8	16.3	510	15	5.1	12.8
7.0	10.1	-	PACl	50	7.5	0	60	3	22	36	14.5	31320	9.8	16.3	510	15	5.1	12.8
7.0	9.9	-	PACl	30	5	0	60	3	22.5	40	14.5	34800	9.8	16.3	500	15	5.1	12.8
7.0	9.9	-	PACl	30	5	0	60	3	22.5	40	14.5	34800	9.8	16.3	500	15	5.1	12.8
7.0	9.9	-	PACl	40	5	0	60	3	22.5	40	14.5	34800	9.8	16.3	500	15	5.1	12.8
7.0	10.1	-	PACl	30	5	0	60	3	22.5	40	14.5	34800	9.8	16.3	500	15	5.1	12.8
7.0	10.1	-	PACl	40	5	0	60	3	22.5	40	14.5	34800	10.6	17.7	490	15	5.1	12.8
7.0	10.1	-	PACl	30	5	0	60	3	34	88	14.5	76560	10.6	17.7	490	15	5.1	12.8
7.0	10.1	-	PACl	30	5	0	60	3	34	88	14.5	76560	10.6	17.7	490	15	5.1	12.8
7.0	10.1	-	PACl	30	5	0	60	3	20	30	14.5	26100	11.4	19.0	490	15	5.1	12.8
7.1	10.1	-	PACl	30	5.5	0	90	2	20	30	9.7	17400	11.4	12.7	500	15	7.7	8.5
7.0	10.1	-	PACl	30	5.5	0	90	2	34	88	9.7	51040	11.4	12.7	500	15	7.7	8.5
7.1	10.1	-	PACl	30	5.5	0	90	2	20	30	9.7	17400	11.4	12.7	490	15	7.7	8.5
6.9	9.9	-	PACl	30	5.5	0	90	2	34	88	9.7	51040	11.4	12.7	490	15	7.7	8.5
6.9	9.9	-	PACl	30	5	0	60	3	20	30	14.5	26100	11.4	19.0	490	15	5.1	12.8
6.9	9.9	-	PACl	20	5	0	60	3	20	30	14.5	26100	11.4	19.0	490	15	5.1	12.8
7.0	10.1	-	PACl	20	5	0	60	3	20	30	14.5	26100	11.4	19.0	500	15	5.1	12.8
7.0	10.1	-	PACl	10	5	0	60	3	20	30	14.5	26100	11.4	19.0	500	15	5.1	12.8
7.0	10.1	-	PACl	20	5	0	60	3	20	30	14.5	26100	11.4	19.0	500	15	5.1	12.8
6.9	9.9	-	FeCl3	10	5	0	60	3	20	30	14.5	26100	12.1	20.2	490	15	5.1	12.8
6.9	9.9	-	FeCl3	20	10	0	60	3	20	30	14.5	26100	12.1	20.2	490	15	5.1	12.8
6.9	9.9	-	FeCl3	15	yes	0	60	3	20	30	14.5	26100	12.1	20.2	490	15	5.1	12.8
7.0	9.9	-	FeCl3	15	7.5	0	60	3	22	30	14.5	26100	11.4	19.0	500	15	5.1	12.8
7.1	10.1	-	FeCl3	12	5	0	80	3	20	30	10.9	19575	11.4	14.3	480	15	6.9	9.6
7.1	10.1	-	FeCl3	12	10	0	80	3	20	30	10.9	19575	11.4	14.3	480	15	6.9	9.6
7.0	9.9	-	FeCl3	12	7.5	0	80	3	22	36	10.9	23490	11.4	14.3	500	15	6.9	9.6
7.0	9.9	-	FeCl3	12	7.5	0	80	3	22	36	10.9	23490	11.4	14.3	480	15	6.9	9.6
7.0	10.1	-	FeCl3	16	18	0	80	3	22	36	10.9	23490	11.7	14.6	480	15	6.9	9.6
7.0	10.1	-	FeCl3	16	18	0	80	3	22	36	10.9	23490	11.4	14.3	480	15	6.9	9.6
7.0	10.1	-	FeCl3	16	16	0	80	3	22	36	10.9	23490	11.4	14.3	470	15	6.9	9.6
7.0	10.1	-	FeCl3	8	7.5	0	80	3	22	36	10.9	23490	11.4	14.3	470	15	6.9	9.6
7.0	10.1	-	FeCl3	16	16.5	0	90	2	20	30	9.7	17400	11.4	12.7	470	15	7.7	8.5
7.0	10.1	-	FeCl3	16	16.5	0	90	2	30	70	9.7	40600	11.4	12.7	470	15	7.7	8.5
7.0	10.1	-	FeCl3	16	20	0	60	3	20	30	14.5	26100	11.4	19.0	470	15	5.1	12.8
7.0	10.1	-	FeCl3	16	18	0	80	3	22	37	10.9	24143	11.4	14.3	470	15	6.9	9.6
7.0	10.1	-	FeCl3	16	21	0	60	3	30	70	14.5	60900	11.7	19.5	480	15	5.1	12.8
7.0	10.1	-	FeCl3	12	15.5	0	80	3	20	30	10.9	19575	11.7	14.6	460	15	6.9	9.6
7.0	10.1	-	FeCl3	12	yes	0	80	3	20	30	10.9	19575	11.7	14.6	460	15	6.9	9.6
7.0	10.1	-	FeCl3	12	14	0	80	3	20	30	10.9	19575	11.0	13.8	420	15	6.9	9.6
7.0	10.1	-	FeCl3	16	yes	0	60	3	20	30	14.5	26100	11.4	19.0	420	15	5.1	12.8

Table C3

		Post Ozonation	Coagulation													
	Date Collected @	O_3 Residual	Turbidity	% Turbidity Removal	Particles						pH	Colour	% Colour Removal	O_3 Residual	UV_{254}	% UV_{254} Removal
					>2 µm	>4 µm	>8 µm	>16 µm	>32 µm	>60 µm						
Run #	MM:DD/hh:mm	mg/L	NTU		#/mL	#/mL	#/mL	#/mL	#/mL	#/mL		ACU		mg/L	cm^{-1}	
0726a	07:26/14:00	0.35	0.27	-5	423	183	80	1	0	0	6.3	-	-	0.05	-	-
0727b	?	0.88	0.24	-2	426	193	87	1	0	0	6.3	-	-	0.45	-	-
0728c	07:28/14:30	0.62	-	-	-	-	-	-	-	-	-	-	-	0.42	-	-
0804d	never	-	-	-	-	-	-	-	-	-	6.7	-	-	-	-	-
0805e	?	0.18	0.50	-107	475	209	89	1	0	0	6.5	-	-	0.10	-	-
0808f	never	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
0808g	?	-	-	-	-	-	-	-	-	-	6.8	-	-	0.05	-	-
0808h	08:08/13:30	-	0.51	-243	379	160	43	0	0	0	6.5	-	-	0.21	-	-
0808i	08:10/10:30	-	0.60	-	503	220	67	0	0	0	7.0	-	-	-	-	-
0810j	?	-	0.38	-43	478	214	67	0	0	0	6.9	-	-	-	-	-
0810k	08:11/09:00	0.22	0.29	-	437	208	68	1	0	0	6.5	-	-	0.10	-	-
0811l	08:11/13:45	0.27	0.47	-100	385	170	53	0	0	0	6.7	-	-	0.11	-	-
0817m	08:17/14:00	0.05	0.98	-242	379	187	90	1	0	0	6.8	-	-	0.00	-	-
0817n	08:18/09:40	-	0.77	-	488	219	68	0	0	0	7.0	-	-	-	-	-
0818o	08:18/15:00	0.04	0.80	-286	403	182	53	0	0	0	6.5	-	-	0.01	-	-
0818p	08:19/10:55	0.04	0.77	-	402	190	58	0	0	0	6.6	-	-	0.00	-	-
0819q	08:19/13:45	0.15	0.83	-321	393	192	51	1	0	0	6.7	-	-	0.09	-	-
0820r	08:20/14:30	-	0.88	-218	779	343	108	1	0	0	6.8	-	-	-	-	-
0820s	08:21/12:20	0.53	0.18	-	324	145	42	1	0	0	-	-	-	0.30	-	-
0821t	08:23/11:00	0.22	0.20	2	301	138	42	0	0	0	7.1	-	-	0.04	-	-
0823u	08:24/10:00	0.04	0.20	0	325	155	49	1	0	0	7.0	-	-	0.02	-	-
0824v	08:24/11:40	-	0.22	-11	331	166	55	0	0	0	-	-	-	-	-	-
0908w	09:08/09:15	-	1.02	-74	1244	536	149	2	1	1	6.8	-	-	-	-	-
0908x	09:08/15:00	0.03	1.16	-116	1155	445	93	0	0	0	6.6	-	-	0.01	-	-
0909y	09:10/09:40	0.16	1.02	-	887	395	80	0	0	0	6.4	-	-	0.00	-	-
0910z	09:12/13:00	-	0.93	-81	881	408	121	1	0	0	-	-	-	-	-	-
0912aa	09:13/09:15	0.07	0.70	-61	831	284	71	1	0	0	5.0	-	-	0.01	-	-
0913ab	09:13/15:05	-	0.97	-143	800	332	94	1	0	0	6.4	-	-	-	-	-
0913ac	09:14/08:30	0.05	0.75	-	588	271	75	1	0	0	6.3	-	-	0.01	-	-
0914ad	09:14/14:15	0.31	0.58	-81	540	222	58	1	0	0	6.2	-	-	0.15	0.016	77
0914ae	09:15/09:30	0.35	0.86	-	535	230	66	1	0	0	6.1	-	-	0.03	0.012	83
0915af	09:15/14:40	-	0.93	-106	717	311	97	1	0	0	6.5	-	-	-	0.024	59
0915ag	09:16/10:40	-	0.81	-	579	266	87	1	0	0	6.7	-	-	-	0.072	-24
0916ah	09:16/14:30	0.01	0.51	-48	490	222	70	1	0	0	6.8	-	-	0.00	0.030	62
0916ai	09:17/09:00	-	0.82	-	612	264	82	1	0	0	6.4	-	-	-	0.015	-
0917aj	09:20/08:30	0.00	0.79	-161	600	277	94	2	0	0	5.5	-	-	-	0.027	83
0920ak	09:20/14:22	-	0.79	-155	483	226	67	1	0	0	-	-	-	-	0.023	41
0920al	09:21/09:55	0.01	0.76	-	496	221	70	1	0	0	6.6	-	-	0.00	0.080	-54
0921am	09:21/14:00	0.01	0.70	-116	448	192	60	1	0	0	6.5	-	-	-	0.008	86
0921an	09:22/10:30	0.01	0.70	-	415	184	60	0	0	0	6.7	-	-	-	-	-
0922ao	09:22/15:00	0.01	0.76	-151	441	196	64	1	0	0	6.6	-	-	0.00	-	-
0922ap	09:23/09:47	0.02	0.73	-	506	223	70	1	0	0	6.5	-	-	-	0.029	-
0923aq	09:24/08:40	0.03	0.66	-120	390	167	58	0	0	0	6.8	-	-	0.00	-	-
0927ar	09:28/09:30	-	0.49	-90	562	252	81	1	0	0	6.8	-	-	-	0.026	-
0928as	09:28/12:40	0.03	0.46	-40	442	189	64	1	0	0	6.7	-	-	0.02	0.019	63
0928at	09:28/15:10	-	0.39	-	417	200	64	1	0	0	6.7	-	-	-	0.036	27
0929au	10:01/09:30	-	0.35	-	594	288	97	1	0	0	6.8	-	-	-	0.066	-
1001av	10:01/13:00	-	0.56	-77	594	275	87	1	0	0	6.6	20	-43	-	0.019	86
1001aw	10:02/12:45	-	0.32	-	597	292	96	1	0	0	6.8	20	-	-	0.058	-4
1002ax	10:04/09:15	0.03	0.49	-44	512	246	81	1	0	0	6.5	7	42	0.01	0.008	90
1004ay	10:04/15:25	0.06	0.62	-102	588	275	93	1	0	0	6.3	12	29	0.01	0.007	89
1004az	10:05/10:00	0.04	0.38	-	556	279	92	1	0	0	6.5	8	-	0.01	0.037	40
1005ba	10:05/13:30	0.03	0.57	-61	553	271	86	1	0	0	6.5	10	29	0.01	0.007	89
1005bb	10:06/08:45	0.01	0.51	-	533	249	83	1	0	0	6.2	10	-	0.00	0.009	85
1006bc	10:06/13:30	-	0.45	-39	478	234	76	1	0	0	6.9	8	62	-	0.039	28
1006bd	10:07/09:30	0.02	0.57	-	491	241	73	1	0	0	6.4	10	-	0.01	0.004	90
1015be	10:15/14:30	0.01	0.51	-45	538	264	92	1	0	0	6.6	16	25	0.00	0.064	23
1015bf		-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
1016bg	10:16/13:30	-	0.76	-66	747	345	110	1	0	0	-	23	4	-	0.009	88
1016bh	10:16/15:15	0.02	0.65	-	778	363	112	2	0	0	6.5	17	-	0.01	0.050	31
1016bi		-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
1018bj	10:19/10:00	0.01	0.79	-	673	322	98	1	0	0	5.8	16	-	0.00	0.014	-
1019bk	10:19/13:00	-	0.73	-61	790	377	117	1	0	0	6.5	17	35	-	0.043	48
1019bl	10:19/16:15	-	1.37	-	902	423	126	1	0	0	6.3	14	-	-	0.015	82
1019bm	10:20/08:40	-	0.74	-	-	-	-	-	-	-	6.5	19	-	-	0.039	54
1020bn	10:20/15:00	-	1.25	-221	940	486	134	2	0	0	-	23	-36	-	0.008	89
1020bo	10:21/10:00	0.00	1.10	-	870	403	123	2	0	0	6.4	13	-	-	0.005	-
1021bp	10:21/14:00	-	1.13	-196	768	336	97	1	0	0	6.3	7	63	-	0.004	94
1021bq	10:23/12:30	-	0.77	-	-	-	-	-	-	-	6.5	14	-	-	0.019	73
1023br	10:23/15:30	-	1.15	-186	743	364	103	1	0	0	5.8	13	41	-	0.020	73
1023bs	10:25/10:30	-	1.08	-	796	375	118	2	0	0	5.9	13	-	-	0.005	93
1025bt	10:25/15:20	-	0.99	-178	1101	886	187	3	0	0	-	15	21	0.02	0.017	89
1026bu	10:26/13:10	-	1.10	-186	710	380	114	1	0	0	6.2	19	-12	-	0.008	92
1026bv	10:26/16:05	0.08	1.00	-	645	304	92	2	0	0	6.2	9	-	0.01	0.006	92
1029bw	10:29/12:45	0.10	1.27	-83	1279	667	209	5	0	0	6.2	11	52	0.01	0.003	96
1029bx	10:29/15:30	0.02	1.11	-	1063	584	192	4	0	0	5.9	13	-	0.01	0.012	85
1103by	11:03/12:30	-	2.12	-120	3637	1485	503	8	0	0	5.5	21	0	-	0.021	75
1103bz	11:03/15:30	-	2.86	-	4459	2767	1246	66	8	1	5.8	23	-	-	0.023	76
1104ca	11:04/14:40	-	3.45	-321	5854	3515	1844	66	8	1	5.7	24	-14	-	0.031	71
1108cb	11:08/16:30	-	4.02	-107	5518	2886	955	6	0	0	-	31	-15	-	0.018	84
1109cc	11:09/12:50	-	3.72	-83	4700	2483	762	5	0	0	-	28	0	-	0.017	85
1109cd	11:09/15:15	0.01	3.47	-	4790	2603	796	5	0	0	-	27	-	0.00	0.021	82
1110ce	11:10/12:00	-	3.70	-157	4625	2340	680	4	0	0	5.3	28	-4	-	0.021	82
1110cf	11:10/12:30	-	3.86	-	4176	2124	685	4	0	0	-	34	-	-	0.030	72
1111cg	11:11/12:00	-	3.34	-137	3730	1906	694	7	0	0	-	36	-48	-	0.010	91
1111ch	11:11/15:00	-	2.80	-	3675	1967	690	5	0	0	-	32	-	-	0.041	63
1112ci	11:12/13:45	-	2.50	-47	4000	2104	683	7	0	0	-	34	-10	-	0.061	48
1115cj	11:15/13:00	-	4.42	-143	4763	2457	807	3	0	0	-	31	-11	-	0.023	82
1115ck	11:15/15:36	-	4.20	-	5045	2644	777	4	0	0	-	32	-	-	-	
1116cl		-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
1117cm	11:17/11:05	-	4.42	-100	5989	2816	824	6	0	0	5.9	32	-14	-	0.020	82
1117cn	11:17/13:05	-	4.28	-	-	-	-	-	-	-	6.1	31	-	-	0.021	81
1117co	11:17/14:15	-	3.99	-	5248	2746	798	3	0	0	5.8	31	-	-	0.004	78
1117cp	11:17/15:30	-	3.85	-	4988	2556	725	3	0	0	5.8	32	-	-	0.038	78
1117cq	11:17/16:20	-	3.79	-	4905	2515	710	2	0	0	5.9	33	-	-	0.038	75
1118cr	11:18/10:35	-	4.06	-93	4636	2460	690	3	0	0	5.8	33	-18	-	0.024	79
1118cs	11:18/12:05	-	3.89	-	4618	2404	692	3	0	0	5.7	34	-	-	0.023	79
1118ct	11:18/13:30	-	4.11	-	4773	2358	640	3	0	0	5.8	34	-	-	0.023	79
1118cu	11:18/14:50	-	4.02	-	4682	2459	672	2	0	0	5.8	36	-	-	0.025	78
1118cv		-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
1120cw		-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
1124cx	11:24/10:15	-	1.75	-40	3089	1488	368	2	0	0	6.6	36	-21	-	0.050	47
1124cy	11:24/12:00	-	1.73	-	3035	1394	364	1	0	0	6.5	33	-	-	0.008	92
1124cz	11:24/13:30	-	1.64	-	2665	1310	336	1	0	0	6.4	36	-	-	0.008	92
1124da	11:24/14:40	-	1.53	-	2873	1349	344	1	0	0	6.3	36	-	-	0.018	81
1125db	11:25/11:25	-	1.86	-64	2881	1361	358	2	0	0	6.3	30	-3	-	0.010	90
1125dc	11:25/13:00	-	1.38	-	2571	1161	284	1	0	0	6.3	22	-	-	0.007	96
1125dd	11:25/14:35	-	1.30	-	2565	1167	281	1	0	0	6.1	24	-	-	0.010	90
1126de	11:26/09:30	-	1.34	-	2413	1087	271	1	0	0	6.3	32	-	-	0.010	90
1126df	11:26/12:00	-	1.20	-36	2236	1031	288	1	0	0	6.0	31	-11	-	0.008	88
1126dg	11:26/13:15	-	1.36	-	2196	1001	248	1	0	0	6.2	-	-	-	0.007	91
1126dh	11:26/15:20	-	1.33	-	2138	858	253	0	0	0	6.3	22	-	-	0.008	90
1126di	11:27/12:35	-	1.30	-	2001	1059	266	0	0	0	-	28	-	-	0.009	88
1129dj	11:29/11:00	-	1.36	-72	2074	963	290	3	0	0	6.5	27	4	-	0.010	88
1129dk	11:29/13:30	-	1.36	-	1976	887	239	2	0	0	6.4	30	-	-	0.005	94

Table C3 cont.

1129dl	11:29/15:40	-	1.45	-	1968	896	232	2	0	0	6.5	34	-	-	0.005	94
1130dm	11:30/11:45	-	1.22	-71	1886	835	219	2	0	0	6.4	25	7	-	0.010	89
1130dn	11:30/14:10	-	1.21	-	1617	716	189	5	0	0	-	32	-	-	0.009	90
1130do	12:01/09:30	-	1.20	-	1596	724	189	1	0	0	6.5	32	-	-	0.012	87
1201dp	12:01/12:20	-	1.09	-72	1617	716	189	5	0	0	6.5	27	7	-	0.066	37
1201dq	none	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
1201dr	12:01/15:35	-	1.06	-	1340	591	156	1	0	0	6.5	29	-	-	0.017	80
1202ds	12:02/11:40	-	2.12	-267	1781	829	228	2	0	0	6.1	60	-114	-	0.112	-26
1202dt	12:02/13:45	-	1.14	-	1950	973	307	3	0	0	5.8	>60	-	-	0.085	27
1202du	12:02/15:50	-	1.54	-	1747	834	236	2	0	0	6.4	60	-	-	0.023	74
1203dv		-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
1204dw	12:04/12:30	-	1.84	-305	1464	699	209	3	0	0	-	70	-112	-	0.014	83
1204dx	12:04/15:00	-	2.32	-	1508	686	210	3	0	0	-	60	-	-	0.017	79
1206dy	12:06/13:30	-	1.39	-233	1849	823	263	4	0	0	5.9	75	-178	-	0.028	74
1206dz	12:06/16:00	-	1.53	-	1305	625	167	1	0	0	6.0	70	-	-	0.023	74
1207ea	12:07/13:00	-	2.47	-607	1508	718	218	5	0	0	6.3	80	-196	-	0.005	94
1207eb	12:07/14:45	-	2.57	-	1485	698	183	3	0	0	6.5	80	-	-	0.007	91
1207ec	12:07/16:20	-	2.81	-	1318	607	172	3	0	0	6.4	80	-	-	0.009	89
1208ed	12:08/10:30	-	1.67	-	1754	865	284	6	0	0	6.5	80	-	-	0.103	-
1208ee	12:08/12:45	-	2.82	-610	1518	706	242	6	0	0	6.5	80	-187	-	0.014	82
1208ef	12:08/14:10	-	2.96	-	1412	644	184	4	0	0	6.4	80	-	-	0.014	82
1208eg	12:08/15:30	-	2.47	-	1297	574	159	2	0	0	6.4	80	-	-	0.015	80
1208eh	12:09/08:20	-	2.64	-	1258	569	165	2	0	0	6.4	80	-	-	0.008	-
1209ei	12:09/12:30	-	2.41	-651	1431	633	161	1	0	0	6.3	80	-158	-	0.009	87
1209ej	12:10/08:45	-	2.27	-	1947	905	280	4	0	0	6.4	80	-	-	0.009	87
1210ek	12:10/12:05	-	2.33	-581	1319	617	162	3	0	0	6.4	80	-186	-	0.016	77
1213el	12:14/10:35	-	2.02	-443	-	-	-	-	-	-	6.0	80	-186	-	0.008	93
1214em	12:15/10:45	-	2.38	-668	2708	1374	465	9	1	0	6.4	80	-200	-	0.004	93

Table C3 cont.

				Particles						Log Particle Removal (from raw)						DAF
Run #	Turbidity NTU	% Turbidity Removal (from raw)	% Turbidity Removal (from coag)	>2 µm #/mL	>4 µm #/mL	>8 µm #/mL	>16 µm #/mL	>32 µm #/mL	>50 µm #/mL	>2 µm	>4 µm	>8 µm	>16 µm	>32 µm	>50 µm	>2 µm
0726a	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
0727b	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
0729c	0.67	-153	-	461	196	53	1	0	0	0.017	0.094	0.152	-0.263	-	-	-
0804d	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
0805e	0.50	-107	0	403	184	49	1	0	0	0.044	0.080	0.214	0.000	-	-	0.071
0805f	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
0806g	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
0809h	1.21	-415	-50	423	166	45	0	0	0	-0.026	0.052	0.136	-	-	-	-0.048
0809i	0.22	-	64	205	96	33	1	0	0	-	-	-	-	-	-	0.390
0810j	0.48	-83	-28	664	266	75	1	0	0	-0.238	-0.163	-0.095	-0.301	-	-	-0.145
0810k	0.32	-	-11	369	162	44	0	0	0	-	-	-	-	-	-	0.073
0811l	0.58	-148	-24	444	171	44	0	0	0	0.000	0.089	0.201	0.778	-	-	-0.062
0817m	0.53	-163	23	397	180	51	0	0	0	-0.020	0.012	0.067	0.477	-	-	-0.019
0817n	0.68	-	12	482	199	61	0	0	0	-	-	-	-	-	-	0.003
0818o	0.50	-144	37	331	129	37	0	0	0	0.068	0.161	0.245	0.523	-	-	0.086
0818p	0.36	-	53	236	96	25	0	0	0	-	-	-	-	-	-	0.232
0819q	0.53	-167	36	358	126	32	0	0	0	0.010	0.143	0.392	0.845	-	-	0.040
0820r	0.22	-5	67	168	67	20	0	0	0	0.326	0.413	0.487	0.301	-	-	0.688
0820s	0.19	-	-6	286	122	34	1	0	0	-	-	-	-	-	-	0.054
0821t	0.18	13	12	285	127	38	0	0	0	0.109	0.183	0.253	-	-	-	0.024
0823[illegible]	0.18	10	10	307	148	48	0	0	0	0.053	0.091	0.122	-	-	-	0.025
0824v	0.23	-19	-7	421	190	62	0	0	0	-0.067	0.002	0.040	-0.125	-	-	-0.104
0908w	0.25	57	75	240	103	34	1	0	0	0.706	0.725	0.607	0.073	-	-	0.715
0909x	0.42	23	64	397	146	38	0	0	0	0.447	0.518	0.501	0.146	-	-	0.463
0909y	0.44	-	57	384	142	30	0	0	0	-	-	-	-	-	-	0.387
0910z	0.88	-81	5	519	261	85	1	0	0	0.245	0.175	0.094	-0.222	0.000	0.000	0.229
0912aa	0.71	-63	-1	393	146	36	0	0	0	0.261	0.329	0.403	0.845	-	-	0.206
0913ab	0.62	-57	36	402	171	52	1	0	0	0.219	0.239	0.223	-0.243	-0.477	-	0.299
0913ac	0.57	-	25	426	167	48	1	0	0	-	-	-	-	-	-	0.139
0914ad	0.64	-72	-7	659	264	68	1	0	0	-0.061	0.003	0.077	0.000	-	-	-0.086
0914ae	0.35	-	60	191	76	22	0	0	0	-	-	-	-	-	-	0.446
0915af	0.35	2	63	123	46	11	0	0	0	0.631	0.738	0.848	0.954	-	-	0.765
0915ag	0.56	-	-9	652	298	86	2	0	0	-	-	-	-	-	-	-0.052
0916ah	0.52	-52	-2	494	237	69	1	0	0	-0.023	-0.037	0.039	0.331	-	-	0.004
0916ai	0.27	-	67	124	53	23	0	0	0	-	-	-	-	-	-	0.693
0917aj	0.50	-64	37	176	69	19	0	0	0	0.403	0.491	0.588	-	-	-	0.532
0920ak	0.27	14	66	186	65	19	0	0	0	0.342	0.484	0.568	0.477	-	-	0.414
0920al	0.29	-	61	226	95	25	0	0	0	-	-	-	-	-	-	0.342
0921am	0.26	20	63	180	71	17	0	0	0	0.349	0.427	0.590	1.146	-	-	0.395
0921an	0.30	-	57	299	103	28	0	0	0	-	-	-	-	-	-	0.142
0922ao	0.28	7	63	118	49	16	0	0	0	0.543	0.590	0.622	0.778	-	-	0.571
0922ap	0.24	-	67	91	36	12	0	0	0	-	-	-	-	-	-	0.746
0923aq	0.25	16	62	177	77	26	0	0	0	0.346	0.408	0.404	0.875	-	-	0.353
0927ar	0.36	-10	27	236	89	26	1	0	0	0.296	0.390	0.494	0.410	-	-	0.370
0928as	0.41	-24	12	383	168	49	1	0	0	0.096	0.141	0.232	0.294	-	-	0.063
0928at	0.39	-	-1	464	220	72	1	0	0	-	-	-	-	-	-	-0.047
0929au	0.39	-	-9	648	301	98	2	0	0	-	-	-	-	-	-	-0.038
1001av	0.24	25	57	236	97	30	1	0	0	0.351	0.430	0.509	0.388	-	-	0.401
1001aw	0.33	-	-2	578	281	93	2	0	0	-	-	-	-	-	-	0.014
1002ax	0.17	50	65	144	64	17	0	0	0	0.588	0.633	0.775	1.000	-	-	0.550
1004ay	0.21	33	67	202	99	39	1	0	0	0.436	0.460	0.444	0.026	-	-	0.464
1004az	0.38	-	2	461	230	76	1	0	0	-	-	-	-	-	-	0.082
1005ba	0.17	47	71	106	59	17	0	0	0	-	-	-	-	-	-	0.717
1005bb	0.16	-	68	75	31	10	0	0	0	-	-	-	-	-	-	0.854
1006bc	0.43	-31	6	513	253	89	2	0	0	-0.001	0.036	0.063	0.048	-	-	-0.031
1006bd	0.13	-	77	75	32	10	0	0	0	-	-	-	-	-	-	0.818
1015be	0.56	-60	-8	588	274	90	2	0	0	0.001	0.030	0.063	0.023	-	-	-0.038
1015bf	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
1016bg	0.22	43	71	181	75	19	1	0	0	0.552	0.631	0.749	0.398	-	-	0.615
1016bh	0.63	-	3	697	332	104	1	0	0	-	-	-	-	-	-	0.048
1018bi	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
1018bj	0.26	-	67	251	106	34	0	0	0	-	-	-	-	-	-	0.428
1019bk	0.75	-86	-3	955	458	136	2	0	0	-0.093	-0.066	-0.026	-0.075	-	-	-0.082
1019bl	0.53	-	62	252	111	32	0	0	0	-	-	-	-	-	-	0.564
1019bm	0.79	-	-7	897	423	127	1	0	0	-	-	-	-	-	-	-
1020bn	1.60	-311	-28	485	235	78	1	0	0	0.179	0.195	0.175	0.176	-	-	0.292
1020bo	0.33	-	70	199	79	25	1	0	0	-	-	-	-	-	-	0.640
1021bp	0.40	-5	65	167	66	18	0	0	0	0.622	0.719	0.819	1.000	-	-	0.682
1021bq	0.79	-	-3	629	270	74	0	0	0	-	-	-	-	-	-	-
1023br	1.32	-238	-15	668	354	121	1	0	0	0.041	0.019	-0.009	0.000	-	-	0.046
1023bs	0.40	-	63	219	105	30	0	0	0	-	-	-	-	-	-	0.554
1025bt	0.66	-85	34	535	229	63	0	0	0	0.060	0.137	0.214	0.439	-	-	0.313
1028bu	0.53	-42	52	479	201	68	1	0	0	0.078	0.163	0.173	-0.051	-	-	0.171
1028bv	0.43	-	57	237	88	26	0	0	0	-	-	-	-	-	-	0.435
1029bw	0.59	10	53	581	257	83	2	0	0	0.398	0.475	0.510	0.493	-	-	0.342
1029bx	1.62	-	-46	1124	543	179	3	0	0	-	-	-	-	-	-	-0.024
1103by	1.19	-23	44	1477	681	228	4	0	0	0.140	0.165	0.109	-0.010	0.602	-	0.284
1103bz	1.51	-	48	2153	1172	475	21	2	0	-	-	-	-	-	-	0.316

DAF

(from raw)			Log Particle Removal (from coag.)						pH	Colour	% Colour Removal	% Colour Removal	O_3 Residual	UV_{254}	% UV_{254} Removal	% UV_{254} Removal
µm	>32 µm	>50 µm	>2 µm	>4 µm	>8 µm	>16 µm	>32 µm	>50 µm		ACU	(from raw)	(from coag.)	mg/L	cm^{-1}	(from raw)	(from coag.)
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
63	-	-	-	-	-	-	-	-	5.7	-	-	-	0.05	-	-	-
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
00	-	-	0.071	0.056	0.079	0.125	-	-	6.5	-	-	-	-	-	-	-
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
-	-	-	-0.048	-0.016	-0.020	-	-	-	-	-	-	-	0.05	-	-	-
-	-	-	0.390	0.359	0.309	-0.602		-	7.0	-	-	-	-	-	-	-
01	-	-	-0.145	-0.093	-0.050	-0.204	-0.301	-	7.0	-	-	-	-	-	-	-
-	-	-	0.073	0.109	0.174	0.699	-	-	6.8	-	-	-	-	-	-	-
78	-	-	-0.062	-0.004	0.077	0.301	-	-	6.8	-	-	-	0.01	-	-	-
77	-	-	-0.019	0.015	-0.002	0.301	-	-	-	-	-	-	0	-	-	-
-	-	-	0.003	0.041	0.047	0.301	-	-	-	-	-	-	-	-	-	-
23	-	-	0.086	0.149	0.154	0.222	-	-	-	-	-	-	0	-	-	-
-	-	-	0.232	0.296	0.347	0.699	-	-	6.7	-	-	-	0	-	-	-
45	-	-	0.040	0.182	0.204	0.778	-	-	6.7	-	-	-	0	-	-	-
01	-	-	0.666	0.712	0.722	0.845	-	-	-	-	-	-	-	-	-	-
-	-	-	0.054	0.075	0.099	-0.138	-	-	-	-	-	-	0.04	-	-	-
-	-	-	0.024	0.029	0.046	-	-	-	-	-	-	-	-	-	-	-
-	-	-	0.025	0.022	0.016	-	-	-	-	-	-	-	-	-	-	-
125	-	-	-0.104	-0.060	-0.050	-0.602	-	-	-	-	-	-	-	-	-	-
073	-	-	0.715	0.718	0.643	0.301	-	-	6.7	-	-	-	-	-	-	-
46	-	-	0.463	0.483	0.388	-0.222	-	-	6.6	-	-	-	0	-	-	-
-	-	-	0.387	0.410	0.418	-0.125	-	-	6.4	-	-	-	0	-	-	-
222	0.000	0.000	0.229	0.193	0.155	0.028	0.301	0.301	-	-	-	-	-	-	-	-
45	-	-	0.206	0.259	0.291	0.845	-	-	-	-	-	-	0	-	-	-
243	-0.477	-	0.299	0.287	0.256	0.000	-	-	-	-	-	-	-	-	-	-
-	-	-	0.139	0.209	0.194	0.155	-	-	-	-	-	-	-	-	-	-
000	-	-	-0.086	-0.076	-0.072	-0.058	0.000	0.000	-	-	-	-	0.01	0.016	77	0
-	-	-	0.446	0.480	0.478	0.903	-	-	-	-	-	-	-	0.01	-	17
54	-	-	0.765	0.827	0.929	1.000	-	-	6.5	-	-	-	-	0.024	59	0
-	-	-	-0.052	-0.049	0.002	-0.109	-	-	-	-	-	-	-	0.065	-	10
31	-	-	0.004	-0.028	0.003	-0.067	-	-	-	-	-	-	-	0.046	41	-53
-	-	-	0.693	0.698	0.560	-	-	-	-	-	-	-	-	0.019	-	-27
-	-	-	0.532	0.605	0.692	-	-	-	-	-	-	-	-	0.028	61	-4
77	-	-	0.414	0.539	0.551	0.426	-	-	6.6	-	-	-	-	0.02	49	13
-	-	-	0.342	0.367	0.440	1.000	-	-	-	-	-	-	-	0.06	-	0
46	-	-	0.395	0.430	0.540	0.903	-	-	-	-	-	-	-	0.026	68	7
-	-	-	0.142	0.253	0.335	-	-	-	-	-	-	-	-	-	-	-
78	-	-	0.571	0.598	0.615	0.954	-	-	-	-	-	-	-	-	-	-
-	-	-	0.746	0.789	0.765	1.000	-	-	6.5	-	-	-	-	0.024	-	17
75	-	-	0.353	0.387	0.355	0.301	-	-	6.7	-	-	-	-	-	-	-
10	-	-	0.370	0.451	0.499	0.234	-	-	6.9	-	-	-	-	0.042	-	-50
94	-	-	0.063	0.075	0.122	0.180	-	-	6.7	-	-	-	-	0.016	69	16
-	-	-	-0.047	-0.040	-0.048	0.000	-	-	-	-	-	-	-	0.035	-	8
-	-	-	-0.038	-0.018	-0.003	-0.051	0.000	-	-	-	-	-	-	0.056	-	0
88	-	-	0.401	0.454	0.457	0.160	-	-	6.6	8	43	60	-	0.013	77	32
-	-	-	0.014	0.017	0.014	-0.189	-	-	-	18	-	10	-	0.058	-	0
000	-	-	0.550	0.585	0.686	0.778	-	-	-	5	58	29	0	0.005	92	17
026	-	-	0.464	0.443	0.382	-0.058	-	-	6.3	3	82	75	-	0.006	90	14
-	-	-	0.082	0.083	0.081	0.160	-	-	-	7	-	13	-	0.033	-	11
-	-	-	0.717	0.664	0.699	0.727	-	-	-	5	64	50	-	0.006	90	14
-	-	-	0.854	0.896	0.916	0.602	-	-	6.2	4	-	60	-	0.008	-	11
048	-	-	-0.031	-0.034	-0.061	-0.189	-	-	-	9	57	-13	-	0.025	54	36
-	-	-	0.818	0.883	0.867	1.000	-	-	6.5	4	-	60	-	0.004	-	0
023	-	-	-0.038	-0.015	0.013	-0.214	-	-	-	18	25	0	-	0..057	-	-
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
390	-	-	0.615	0.664	0.762	0.398	-	-	-	8	67	65	-	0.012	83	-33
-	-	-	0.048	0.039	0.034	0.054	-	-	-	15	-	12	-	0.047	-	6
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
-	-	-	0.428	0.483	0.463	0.380	-	-	-	9	-	44	-	0.014	-	0
075	-	-	-0.082	-0.084	-0.065	-0.376	-	-	-	18	31	-6	-	0.065	23	-51
-	-	-	0.564	0.581	0.598	0.778	-	-	-	10	-	29	-	0.014	-	7
-	-	-	-	-	-	-	-	-	-	17	-	11	-	0.034	-	13
176	-	-	0.292	0.290	0.234	0.352	-	-	-	14	18	39	-	0.007	91	13
-	-	-	0.640	0.709	0.697	0.544	-	-	-	2	-	85	-	0.004	-	20
000	-	-	0.662	0.711	0.739	1.041	-	-	-	5	74	29	-	0.004	94	0
-	-	-	-	-	-	-	-	-	-	13	-	7	-	0.013	-	32
000	-	-	0.046	0.000	-0.069	-0.067	-	-	-	14	36	-8	-	0.008	89	60
-	-	-	0.554	0.556	0.591	-	-	-	5.9	4	-	69	-	0.004	-	20
439	-	-	0.313	0.393	0.476	0.978	-	-	-	12	37	20	-	0.016	70	6
051	-	-	0.171	0.252	0.223	0.222	-	-	-	11	35	42	-	0.008	89	-33
-	-	-	0.435	0.537	0.555	1.279	-	-	-	4	-	56	0	0.008	-	-33
493	-	-	0.342	0.414	0.441	0.469	-	-	-	3	87	73	-	0.008	90	-167
-	-	-	-0.024	0.009	0.031	0.089	0.301	-	-	12	-	8	-	0.008	-	33
010	0.602	-	0.284	0.339	0.345	0.202	0.000	-	-	16	24	24	-	0.021	78	0
-	-	-	0.316	0.376	0.420	0.491	0.590	1.114	-	12	-	48	-	0.025	-	-9

Table C3 cont.

1104ca	2.14	-161	38	3284	1897	791	48	4	1	-0.233	-0.328	-0.510	-1.719	-	-	0.212	0.2
1108cb	3.65	-88	9	5646	2814	824	6	0	0	-0.036	0.013	0.077	0.231	-	-	-0.010	0.0
1109cc	3.56	-84	4	4726	2291	659	6	0	0	0.045	0.093	0.145	-0.044	-0.602	-	-0.002	0.0
1109cd	3.43	-	1	4992	2434	686	6	0	0	-	-	-	-	-	-	-0.019	0.0
1110ce	3.64	-153	2	3595	1833	635	12	0	0	0.000	-0.002	-0.074	-0.494	-	-	0.100	0.1
1110cf	4.60	-	-19	3948	2074	758	17	0	0	-	-	-	-	-	-	0.024	0.0
1111cg	2.12	-50	37	2553	1092	303	3	0	0	0.146	0.226	0.269	0.301	-	-	0.165	0.2
1111ch	3.47	-	-24	3511	1978	777	21	0	0	-	-	-	-	-	-	0.043	-0.0
1112ci	3.42	-101	-37	4208	2466	957	17	0	0	-0.018	-0.060	-0.143	-0.387	0.222	-	-0.022	-0.0
1115cj	3.80	-109	14	-	-	-	-	-	-	-	-	-	-	-	-	-	-
1115ck	4.87	-	-16	6921	3568	1027	10	0	0	-	-	-	-	-	-	-0.137	-0.1
1116cl	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
1117cm	3.52	-59	20	3824	1819	521	4	0	0	0.131	0.165	0.164	-0.176	0.000	-	0.147	0.1
1117cn	4.62	-	-8	-	-	-	-	-	-	-	-	-	-	-	-	-	-
1117co	3.41	-	15	4023	2026	627	7	0	0	-	-	-	-	-	-	0.115	0.1
1117cp	3.72	-	3	5292	2800	860	12	0	0	-	-	-	-	-	-	-0.028	-0.0
1117cq	4.79	-	-26	6661	3737	1238	17	0	0	-	-	-	-	-	-	-0.131	-0.1
1118cr	4.62	-119	-13	6684	3461	974	5	0	0	-0.161	-0.173	-0.185	-0.402	-	-	-0.141	-0.1
1118cs	5.10	-	-28	7242	3697	952	4	0	0	-	-	-	-	-	-	-0.168	-0.1
1118ct	4.72	-	-15	6851	3352	878	5	0	0	-	-	-	-	-	-	-0.157	-0.1
1118cu	5.43	-	-35	7931	4112	1107	7	0	0	-	-	-	-	-	-	-0.211	-0.2
1119cv	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
1123cw	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
1124cx	1.79	-43	-2	3632	1811	531	4	0	0	-0.113	-0.138	-0.182	-0.384	-	-	-0.075	-0.0
1124cy	0.29	-	83	679	321	96	1	0	0	-	-	-	-	-	-	0.651	0.6
1124cz	0.34	-	80	382	158	46	1	0	0	-	-	-	-	-	-	0.873	0.9
1124da	4.53	-	-196	4502	3082	1486	30	0	0	-	-	-	-	-	-	-0.195	-0.3
1125db	0.29	73	83	339	144	41	0	0	0	0.872	0.911	0.870	0.544	-	-	0.930	0.9
1125dc	0.35	-	78	535	247	80	1	0	0	-	-	-	-	-	-	0.662	0.6
1125dd	1.19	-	8	1820	1009	373	2	0	0	-	-	-	-	-	-	0.152	0.0
1125de	0.30	-	81	322	134	40	1	0	0	-	-	-	-	-	-	0.874	0.9
1126df	2.04	-117	-70	3314	1995	793	5	0	0	-0.168	-0.283	-0.475	-0.724	-	-	-0.171	-0.2
1126dg	0.26	-	81	440	215	75	1	0	0	-	-	-	-	-	-	0.699	0.6
1126dh	0.24	-	82	363	158	49	1	0	0	-	-	-	-	-	-	0.771	0.7
1126di	0.22	-	84	343	150	47	1	0	0	-	-	-	-	-	-	0.827	0.8
1129dj	0.47	41	66	531	200	45	0	0	0	0.548	0.636	0.716	0.778	-	-	0.592	0.6
1129dk	0.42	-	69	788	284	69	0	0	0	-	-	-	-	-	-	0.399	0.4
1129dl	0.45	-	69	605	229	52	1	0	0	-	-	-	-	-	-	0.512	0.5
1130dm	0.43	40	65	642	248	64	1	0	0	0.391	0.460	0.459	-0.255	-	-	0.464	0.5
1130dn	0.24	-	80	319	140	43	0	0	0	-	-	-	-	-	-	0.705	0.7
1130do	0.37	-	70	513	201	56	1	0	0	-	-	-	-	-	-	0.493	0.5
1201dp	0.50	20	54	319	140	43	0	0	0	0.682	0.709	0.652	0.653	-	-	0.705	0.7
1201dq	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
1201dr	0.54	-	50	647	252	64	0	0	0	-	-	-	-	-	-	0.316	0.3
1202ds	1.99	-263	6	1565	675	168	1	0	0	-0.078	-0.051	-0.023	-0.176	-	-	0.056	0.0
1202dt	3.96	-	-247	5609	3806	1742	13	0	0	-	-	-	-	-	-	-0.459	-0.
1202du	1.12	-	27	1208	489	135	3	0	0	-	-	-	-	-	-	0.160	0.2
1203dv	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
1204dw	0.96	-112	48	1122	418	122	2	0	0	-0.018	0.078	0.072	0.067	-	-	0.116	0.2
1204dx	1.03	-	56	1018	338	89	1	0	0	-	-	-	-	-	-	0.171	0.3
1206dy	1.83	-339	-32	1194	474	120	1	0	0	-0.113	-0.050	-0.023	-0.051	-	-	0.140	0.2
1206dz	1.71	-	-12	1257	461	117	1	0	0	-	-	-	-	-	-	0.016	0.1
1207ea	0.64	-56	74	880	345	105	3	0	0	-0.003	0.069	0.015	-0.447	-	-	0.234	0.3
1207eb	0.87	-	66	1566	578	141	2	0	0	-	-	-	-	-	-	-0.023	0.0
1207ec	1.39	-	47	2270	654	135	1	0	0	-	-	-	-	-	-	-0.236	-0.
1208ed	1.63	-	2	1452	627	167	2	0	0	-	-	-	-	-	-	0.089	0.1
1208ee	1.13	-206	57	1055	359	93	1	0	0	-0.099	0.025	0.057	-0.234	-	-	0.158	0.3
1208ef	1.05	-	59	1300	433	104	1	0	0	-	-	-	-	-	-	0.036	0.1
1208eg	0.81	-	67	1713	715	186	1	0	0	-	-	-	-	-	-	-0.121	-0.
1208eh	0.88	-	67	1555	578	148	1	0	0	-	-	-	-	-	-	-0.091	-0.
1209ei	0.84	-128	65	2776	1080	222	1	0	0	-0.536	-0.466	-0.337	-0.125	-	-	-0.288	-0.
1209ej	0.77	-	66	1142	432	124	3	0	0	-	-	-	-	-	-	0.232	0.2
1210ek	1.27	-271	45	1388	459	112	2	0	0	-0.281	-0.137	-0.081	-0.452	-	-	-0.022	0.1
1213el	0.52	-39	74	-	-	-	-	-	-	-	-	-	-	-	-	-	
1214em	0.77	-154	68	1965	958	308	4	0	0	-0.476	-0.479	-0.476	-0.382	-	-	0.139	0.

-	-	0.212	0.268	0.318	0.257	0.267	0.125	-	21	0	13	-	0.03	72	3
-	-	-0.010	0.026	0.064	0.000	-	-	6.3	24	11	23	-	0.024	79	-33
-0.602	-	-0.002	0.031	0.063	-0.068	-0.602	-	5.6	20	29	29	-	0.019	83	-12
-	-	-0.019	0.012	0.044	-0.131	-0.602	-	-	20	-	26	-	0.019	-	10
-	-	0.100	0.108	0.036	-0.464	-	-	-	20	26	29	-	0.021	82	0
-	-	0.024	0.010	-0.076	-0.579	-	-	-	27	-	21	-	0.024	-	27
-	-	0.165	0.242	0.292	0.416	-	-	6.6	20	23	47	-	0.021	81	-110
-	-	0.043	-0.002	-0.114	-0.661	-	-	5.3	28	-	13	-	0.033	-	20
0.222	-	-0.022	-0.069	-0.159	-0.376	-0.176	-	-	29	6	15	-	0.062	48	-2
-	-	-	-	-	-	-	-	6.1	22	21	29	-	0.02	84	13
-	-	-0.137	-0.130	-0.121	-0.369	-	-	5.9	29	-	9	-	0.025	-	-
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
0.000	-	0.147	0.190	0.199	0.118	-0.301	-	-	29	-4	9	-	0.021	81	-5
-	-	-	-	-	-	-	-	-	31	-	0	-	0.02	-	5
-	-	0.115	0.132	0.104	-0.404	-	-	-	26	-	16	-	0.022	-	8
-	-	-0.028	-0.040	-0.085	-0.628	-	-	-	30	-	6	-	0.025	-	4
-	-	-0.131	-0.172	-0.242	-0.857	-	-	-	31	-	6	-	0.028	-	0
-	-	-0.141	-0.148	-0.144	-0.233	-	-	-	32	-14	3	-	0.026	77	-8
-	-	-0.168	-0.171	-0.139	-0.058	-	-	-	34	-	0	-	0.023	-	0
-	-	-0.157	-0.153	-0.137	-0.316	-	-	-	34	-	0	-	0.023	-	0
-	-	-0.211	-0.223	-0.217	-0.585	-	-	-	35	-	0	-	0.023	-	8
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
-	-	-0.075	-0.092	-0.125	-0.283	-	-	-	-	-	-	-	0.038	60	24
-	-	0.651	0.638	0.569	-0.114	-	-	-	12	-	64	-	0.009	-	-13
-	-	0.873	0.917	0.870	0.041	-	-	-	12	-	67	-	0.006	-	38
-	-	-0.195	-0.359	-0.635	-1.560	-	-	-	30	-	21	-	0.01	-	44
-	-	0.930	0.975	0.944	0.829	-	-	-	14	52	53	-	0.008	92	20
-	-	0.682	0.672	0.550	-0.067	-	-	-	20	-	9	-	0.009	-	-29
-	-	0.152	0.063	-0.123	-0.452	-	-	-	16	-	33	-	0.008	-	20
-	-	0.874	0.908	0.832	-0.222	-	-	-	15	-	53	-	0.008	-	20
-	-	-0.171	-0.287	-0.497	-0.683	-0.477	-	-	28	0	10	-	0.006	92	33
-	-	0.699	0.667	0.517	-0.114	-	-	-	18	-	-	-	0.006	-	14
-	-	0.771	0.780	0.675	-0.447	-	-	-	14	-	36	-	0.009	-	-13
-	-	0.827	0.835	0.751	-0.146	-	-	-	23	-	18	-	0.006	-	33
-	-	0.592	0.684	0.794	1.000	-	-	-	17	39	37	-	0.005	94	50
-	-	0.399	0.494	0.537	1.398	-	-	-	18	-	40	-	0.006	-	-20
-	-	0.512	0.592	0.650	0.434	-	-	-	23	-	4	-	0.003	-	40
-	-	0.464	0.526	0.537	0.388	0.602	-	-	21	22	16	-	0.01	89	0
-	-	0.705	0.708	0.640	-0.301	-	-	6.4	18	-	44	-	0.008	-	11
-	-	0.493	0.556	0.526	-0.046	0.000	0.000	-	21	-	34	-	0.012	-	0
-	-	0.705	0.708	0.640	-0.301	-	-	-	26	10	4	-	0.022	75	60
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
-	-	0.316	0.371	0.389	0.778	-	-	-	26	-	10	-	0.017	-	0
-	-	0.056	0.090	0.134	0.347	-	-	-	65	-132	-8	-	0.061	31	46
-	-	-0.459	-0.592	-0.754	-0.649	-	-	-	>100	-	-	-	0.021	-	68
-	-	0.160	0.232	0.242	-0.047	-	-	-	55	-	31	-	0.011	-	52
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
-	-	0.116	0.223	0.234	0.263	-	-	5.8	50	-52	29	-	0.011	87	21
-	-	0.171	0.307	0.372	0.359	-	-	-	60	-	25	-	0.016	-	6
-	-	0.140	0.239	0.341	0.718	-	-	-	75	-178	0	-	0.005	94	78
-	-	0.016	0.133	0.204	0.000	-	-	-	60	-	14	-	0.008	-	65
-	-	0.234	0.318	0.318	0.252	-	-	-	28	-4	65	-	0.005	94	0
-	-	-0.023	0.062	0.113	0.157	-	-	-	40	-	50	-	0.007	-	0
-	-	-0.236	-0.032	0.105	0.273	-	-	-	48	-	40	-	0.009	-	0
-	-	0.089	0.140	0.200	0.370	-	-	-	80	-	0	-	0.092	-	11
-	-	0.158	0.324	0.417	0.727	-	-	-	55	-83	31	-	0.013	83	7
-	-	0.036	0.173	0.248	0.426	-	-	-	43	-	46	-	0.012	-	14
-	-	-0.121	-0.096	-0.069	0.200	-	-	-	50	-	38	-	0.016	-	-7
-	-	-0.091	-0.007	0.046	0.263	-	-	-	49	-	39	-	0.008	-	0
-	-	-0.288	-0.232	-0.139	0.067	-	-	-	45	-45	44	-	0.01	86	-11
-	-	0.232	0.321	0.323	0.125	-	-	-	50	-	38	-	0.009	-	0
-	-	-0.022	0.128	0.209	0.247	-	-	-	60	-114	25	-	0.016	77	0
-	-	-	-	-	-	-	-	-	40	-43	50	-	0.005	94	17
-	-	0.139	0.157	0.179	0.400	-	0.699	-	42	-68	48	-	0.007	89	-75

Table C3 cont.

	Filtration															
	Turbidity (Bench)			% Turbidity Removal	Particles						Particles (in-line) (Tub<0.1 for >1.0 hr)				Log	
Run #	Filter 4 NTU	Filter 5 NTU	Filter 10 NTU		>2 µm #/mL	>4 µm #/mL	>8 µm #/mL	>16 µm #/mL	>32 µm #/mL	>50 µm #/mL	2-3 µm #/mL	3-5 µm #/mL	5-15 µm #/mL	3-750 µm #/mL	>2 µm	>4 µm
0726a	-	-	0.21	20	150	53	9	0	0	0	-	-	-	-	0.50	0.60
0727b	-	-	0.19	17	143	52	14	0	0	0	-	-	-	-	0.53	0.67
0729c	-	-	0.17	34	18	9	4	0	0	0	-				1.44	1.42
0804d	-	-	-	-	-	-	-	-	-	-	-				-	-
0805e	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
0805f	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
0806g	-	-	-	-	-	-	-	-	-	-	-				-	-
0809h	0.05	-	-	79	19	9	4	0	0	0	3	2	1	2	1.32	1.34
0809i	-	-	-	-	24	9	3	0	0	0	5	2	1	4	-	-
0810j	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
0810k	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
0811l	-	-	-	-	17	7	3	0	0	0	1	0	0	1	1.41	1.46
0817m	0.34	-	-	-66	15	6	2	0	0	0	-	-	-	-	1.41	1.46
0817n	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
0818o	0.07	-	-	67	9	5	2	0	0	0	1	1	0	1	1.63	1.59
0818p	-	-	-	-	-	-	-	-	-	-	-				-	-
0819q	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
0820r	-	-	-	-	26	11	3	0	0	0	2	1	0	2	1.14	1.21
0820s	0.15	-	-	-	37	12	2	0	0	0	-	-	-	-	-	-
0821t	0.15	-	-	26	88	36	9	0	0	0	-	-	-	-	0.62	0.73
0823u	0.15	-	-	28	-	-	-	-	-	-	-	-	-	-	-	-
0824v	-	-	0.16	16	65	25	6	0	0	0	-	-	-	-	0.74	0.88
0908w	-	0.04	-	93	18	8	3	0	0	0	4	1	0	2	1.84	1.82
0909x	0.04	-	-	92	24	11	4	0	0	0	-				1.67	1.66
0909y	0.04	-	-	-	-	-	-	-	-	-	1	0	0	1	-	-
0910z	-	-	-	-	-	-	-	-	-	-	1	0	0	0	-	-
0912aa	0.07	-	-	84	10	4	1	0	0	0	0	0	0	0	1.87	1.89
0913ab	-	-	-	-	-	-	-	-	-	-	3	3	1	4	-	-
0913ac	-	-	0.17	-	18	8	3	0	0	0	-				-	-
0914ad	-	-	0.26	30	7	3	1	0	0	0	-				1.89	1.98
0914ae	0.05	-	-	-	4	1	0	0	0	0	0	0	0	0	-	-
0915af	0.07	-	-	81	15	7	2	0	0	0	-				1.54	1.58
0915ag	0.32	-	-	-	55	25	9	0	0	0	-	-	-	-	-	-
0916ah	0.35	-	-	-3	-	-	-	-	-	-	-	-	-	-	-	-
0916ai	-	-	0.04	-	16	8	3	0	0	0	0	0	0	0	-	-
0917aj	-	-	-	-	25	11	4	0	0	0	0	0	0	0	1.25	1.29
0920ak	0.05	-	-	83	21	8	2	0	0	0	0	0	0	0	1.29	1.41
0920al	0.06	-	-	-	8	3	1	0	0	0	0	0	0	0	-	-
0921am	-	0.06	-	81	17	7	1	0	0	0	1	1	0	1	1.37	1.45
0921an	0.07	-	-	-	-	-	-	-	-	-	0	0	0	0	-	-
0922ao	0.06	-	-	81	14	6	2	0	0	0	0	0	0	0	1.46	1.51
0922ap	0.07	-	-	-	4	1	0	0	0	0	0	0	0	0	-	-
0923aq	0.06	-	-	80	12	5	1	0	0	0	0	0	0	0	1.51	1.63
0927ar	0.09	-	-	73	43	21	7	0	0	0	8	10	4	14	1.04	1.01
0928as	0.18	-	-	44	13	6	1	0	0	0	-	-	-	-	1.58	1.61
0928at	0.29	-	-	-	63	23	7	0	0	0	-	-	-	-	-	-
0929au	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
1001av	0.08	-	-	76	19	8	2	0	0	0	4	3	1	5	1.46	1.50
1001aw	0.33	-	-	-	279	113	35	0	0	0	-	-	-	-	-	-
1002ax	0.06	-	-	82	14	7	3	0	0	0	0	0	0	0	1.61	1.58
1004ay	0.05	-	-	83	16	9	4	0	0	0	0	0	0	0	1.54	1.50
1004az	0.26	-	-	-	66	39	12	0	0	0	-	-	-	-	-	-
1005ba	-	-	0.07	78	15	8	2	0	0	0	0	0	0	0	-	-
1005bb	0.05	-	-	-	9	5	1	0	0	0	0	0	0	0	-	-
1006bc	0.27	-	-	18	65	35	15	0	0	0	-				0.90	0.89
1006bd	0.05	-	-	-	7	3	1	0	0	0	0	0	0	0	-	-
1015be	-	-	0.45	-29	119	48	15	0	0	0	-	-	-	-	0.69	0.78
1015bf	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
1016bg	-	-	0.07	82	20	9	2	0	0	0	78	58	14	32	1.50	1.54
1016bh	-	-	0.41	-	72	37	14	0	0	0	-				-	-
1018bi	-	-	-	-	-	-	-	-	-	-	-				-	-
1018bj	-	-	0.05	-	11	6	2	0	0	0	2	2	0	2	-	-
1019bk	-	0.48	-	-20	107	51	19	0	0	0	-	-	-	-	0.86	0.89
1019bl	0.06	-	-	-	19	10	3	0	0	0	5	2	0	2	-	-
1019bm	0.39	-	-	-	79	37	12	0	0	0	-	-	-	-	-	-
1020bn	-	-	-	-	-	-	-	-	-	-	1	1	0	1	-	-
1020bo	0.05	-	-	-	13	5	2	0	0	0	0	1	0	1	-	-
1021bp	0.05	-	-	88	8	4	1	0	0	0	1	1	0	1	1.93	1.94
1021bq	0.29	-	-	-	25	12	3	0	0	0	-	-	-	-	-	-
1023br	-	-	0.40	-1	13	7	2	0	0	0	-	-	-	-	1.75	1.73
1023bs	-	-	-	-	-	-	-	-	-	-	0	0	0	0	-	-
1025bt	0.37	-	-	-3	24	11	4	0	0	0	-	-	-	-	1.40	1.44
1028bu	0.06	-	-	85	13	6	2	0	0	0	3	1	0	1	1.65	1.72
1028bv	0.04	-	-	-	15	8	3	0	0	0	1	0	0	1	-	-
1029bw	0.06	-	-	90	16	8	3	0	0	0	1	1	0	2	1.97	1.98
1029bx	0.34	-	-	-	16	8	3	0	0	0	-	-	-	-	-	-
1103by	0.07	-	-	93	25	13	5	0	0	0	-	-	-	-	1.91	1.88
1103bz	0.07	-	-	-	24	12	4	0	0	0	-	-	-	-	-	-

Filtration															
n-line) (Tub<0.1 for >1.0 hr)			Log Particle Removal						pH	Colour	% Colour Removal	UV$_{254}$	% UV$_{254}$ Removal	Run Stop	Run Length
-5 µm #/mL	5-15 µm #/mL	3-750 µm #/mL	>2 µm	>4 µm	>8 µm	>16 µm	>32 µm	>50 µm		TCU		cm^{-1}		MM:DD/hh:mm	hh:mm
-	-	-	0.50	0.60	0.81	0.48	-	-	-	-	-	-	-	07:27/14:45	24:22
-	-	-	0.53	0.67	0.74	0.10	-	-	-	-	-	-	-	07:28/09:00	18:15
			1.44	1.42	1.32	0.78	-	-	-	-	-	-	-	07:31/03:20	40:55
			-	-	-	-	-	-	-	-	-	-	-	08:05/09:47	19:47
-	-	-	-	-	-	-	-	-	-	-	-	-	-	08:05/14:55	04:45
-	-	-	-	-	-	-	-	-	-	-	-	-	-	08:06/08:45	17:45
			-	-	-	-	-	-	-	-	-	-	-	08:06/12:30	03:10
2	1	2	1.32	1.34	1.24	0.85	-	-	6.5	-	-	-	-	08:09/15:30	05:10
2	1	4	-	-	-	-	-	-	-	-	-	-	-	08:10/11:00	19:00
-	-	-	-	-	-	-	-	-	-	-	-	-	-	08:10/15:00	03:40
-	-	-	-	-	-	-	-	-	-	-	-	-	-	08:11/09:20	17:50
0	0	1	1.41	1.46	1.42	1.08	-	-	-	-	-	-	-	08:11/14:30	04:40
-	-	-	1.41	1.46	1.41	-	-	-	6.8	-	-	-	-	08:17/14:35	04:35
-	-	-	-	-	-	-	-	-	-	-	-	-	-	08:18/09:55	18:55
1	0	1	1.63	1.59	1.54	1.00	-	-	-	-	-	-	-	08:18/15:30	05:10
			-	-	-	-	-	-	-	-	-	-	-	08:19/11:15	19:25
-	-	-	-	-	-	-	-	-	-	-	-	-	-	08:20/10:45	23:00
1	0	2	1.14	1.21	1.26	0.30	-	-	-	-	-	-	-	08:20/15:00	03:55
-	-	-	-	-	-	-	-	-	-	-	-	-	-	08:21/12:25	21:15
-	-	-	0.62	0.73	0.86	0.70	-	-	-	-	-	-	-	08:23/00:00	34:15
-	-	-	-	-	-	-	-	-	-	-	-	-	-	08:24/10:15	19:30
-	-	-	0.74	0.88	1.07	-	-	-	-	-	-	-	-	08:25/12:00	24:25
1	0	2	1.84	1.82	1.73	-	-	-	6.7	-	-	-	-	09:09/09:45	22:00
			1.67	1.66	1.53	0.85	-	-	-	-	-	-	-	09:09/15:40	04:00
0	0	1	-	-	-	-	-	-	-	-	-	-	-	09:10/10:00	20:05
0	0	0	-	-	-	-	-	-	-	-	-	-	-	09:12/13:00	49:55
0	0	0	1.87	1.89	2.05	-	-	-	-	-	-	-	-	09:13/09:45	19:55
3	1	4	-	-	-	-	-	-	-	-	-	-	-	09:13/15:20	03:05
			-	-	-	-	-	-	-	-	-	-	-	09:14/09:15	17:40
			1.89	1.98	2.11	-	-	-	-	-	-	0.019	73	09:14/15:00	05:15
0	0	0	-	-	-	-	-	-	-	-	-	0.090	-	09:15/10:30	18:50
			1.54	1.58	1.52	-	-	-	6.5	-	-	0.026	55	09:15/15:15	04:20
-	-	-	-	-	-	-	-	-	-	-	-	0.053	-	09:16/11:05	19:40
-	-	-	-	-	-	-	-	-	-	-	-	0.040	49	09:16/15:20	03:30
0	0	0	-	-	-	-	-	-	-	-	-	0.017	-	09:17/09:40	18:05
0	0	0	1.25	1.29	1.28	0.93	-	-	-	-	-	-	-	09:20/09:00	70:55
0	0	0	1.29	1.41	1.60	-	-	-	-	-	-	0.018	54	09:20/15:50	05:55
0	0	0	-	-	-	-	-	-	-	-	-	0.008	-	09:21/10:40	18:30
1	0	1	1.37	1.45	1.66	-	-	-	-	-	-	0.028	65	09:21/15:00	04:00
0	0	0	-	-	-	-	-	-	-	-	-	-	-	09:22/11:25	20:10
0	0	0	1.46	1.51	1.58	-	-	-	-	-	-	-	-	09:22/15:20	03:35
0	0	0	-	-	-	-	-	-	6.5	-	-	0.024	-	09:23/10:30	18:52
0	0	0	1.51	1.63	1.74	-	-	-	-	-	-	-	-	09:24/10:55	24:10
10	4	14	1.04	1.01	1.07	0.78	-	-	-	-	-	0.039	-	09:28/10:15	19:45
-	-	-	1.58	1.61	1.81	-	-	-	6.7	-	-	0.013	75	09:28/12:55	02:25
-	-	-	-	-	-	-	-	-	-	4	-	0.031	-	09:28/15:30	02:27
-	-	-	-	-	-	-	-	-	-	-	-	-	-	10:01/08:50	41:35
3	1	5	1.46	1.50	1.80	-	-	-	6.7	3	79	0.016	71	10:01/13:15	03:20
-	-	-	-	-	-	-	-	-	-	18	-	0.056	-	10:02/13:25	23:20
0	0	0	1.61	1.58	1.56	1.30	-	-	-	2	83	0.004	93	10:04/10:05	44:15
0	0	0	1.54	1.50	1.45	0.93	-	-	-	1	94	0.003	95	10:04/15:25	05:10
-	-	-	-	-	-	-	-	-	-	4	-	0.031	-	10:05/10:45	18:50
0	0	0	-	-	-	-	-	-	6.6	2	86	0.008	86	10:05/13:50	02:43
0	0	0	-	-	-	-	-	-	6.2	2	-	0.005	-	10:06/09:35	19:40
			0.90	0.89	0.83	1.28	-	-	-	8	62	0.041	24	10:06/13:55	04:15
0	0	0	-	-	-	-	-	-	-	3	-	0.005	-	10:07/11:00	20:50
-	-	-	0.69	0.78	0.85	1.28	-	-	-	18	25	0.054	23	10:15/15:10	04:05
-	-	-	-	-	-	-	-	-	-	-	-	-	-	10:16/10:50	19:30
58	14	32	1.50	1.54	1.66	-	-	-	-	4	83	0.014	81	10:16/14:00	02:53
			-	-	-	-	-	-	-	16	-	0.054	-	10:18/10:45	44:30
			-	-	-	-	-	-	-	-	-	-	-	10:18/15:30	04:20
2	0	2	-	-	-	-	-	-	-	3	-	0.011	-	10:19/10:00	18:10
-	-	-	0.86	0.89	0.82	0.73	-	-	-	15	42	0.056	33	10:19/13:50	03:25
2	0	2	-	-	-	-	-	-	-	2	-	0.018	-	10:19/16:30	02:35
-	-	-	-	-	-	-	-	-	-	12	-	0.054	-	10:20/09:05	16:25
1	0	1	-	-	-	-	-	-	-	-	-	-	-	10:20/15:30	06:15
1	0	1	-	-	-	-	-	-	-	2	-	0.004	-	10:21/10:15	18:25
1	0	1	1.93	1.94	2.11	-	-	-	6.4	2	89	0.002	97	10:21/14:25	03:55
-	-	-	-	-	-	-	-	-	-	5	-	0.016	-	10:23/13:15	46:35
-	-	-	1.75	1.73	1.72	-	-	-	-	4	82	0.008	89	10:23/16:00	02:25
0	0	0	-	-	-	-	-	-	-	-	-	-	-	10:25/11:00	43:00
-	-	-	1.40	1.44	1.45	1.04	-	-	-	6	68	0.008	85	10:25/15:30	04:00
1	0	1	1.65	1.72	1.69	0.90	-	-	-	2	88	0.008	89	10:28/13:30	03:20
0	0	1	-	-	-	-	-	-	-	2	-	0.004	-	10:28/16:30	02:55
1	0	2	1.97	1.98	2.01	-	-	-	-	2	91	0.004	95	10:29/13:15	03:15
-	-	-	-	-	-	-	-	-	-	4	-	0.005	-	10:29/15:45	02:25
-	-	-	1.91	1.88	1.80	-	-	-	-	4	81	0.015	84	11:03/13:15	03:25
-	-	-	-	-	-	-	-	-	-	2	-	0.021	-	11:03/15:55	02:40

Table C3 cont.

1104ca	0.07	-	-	91	29	16	6	0	0	0	-	-	-	-	1.83	1.75	1.
1108cb	0.16	-	-	92	38	21	15	0	0	0	-	-	-	-	2.14	2.15	1.
1109cc	0.09	-	-	95	21	11	5	0	0	0	-	-	-	-	2.39	2.41	2.
1109cd	0.09	-	-	-	41	22	8	0	0	0	-	-	-	-	-	-	
1110ce	0.11	-	-	92	15	9	3	0	0	0	-	-	-	-	2.30	2.32	2.
1110cf	0.19	-	-	-	44	23	9	0	0	0	-	-	-	-	-	-	
1111cg	0.43	-	-	69	145	62	14	0	0	0	-	-	-	-	1.39	1.47	1.
1111ch	0.08	-	-	-	105	53	15	0	0	0	-	-	-	-	-	-	
1112ci	0.11	-	-	94	34	18	6	0	0	0	-	-	-	-	2.07	2.08	2.
1115cj	0.12	-	-	93	41	23	9	0	0	0	-	-	-	-	2.02	1.99	1.
1115ck	0.09	-	-	-	72	39	14	0	0	0	-	-	-	-	-	-	
1116cl	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	
1117cm	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	
1117cn	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	
1117co	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	
1117cp	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	
1117cq	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	
1118cr	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	
1118cs	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	
1118ct	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	
1118cu	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	
1119cv	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	
1123cw	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	
1124cx	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	
1124cy	-	-	-	-	-	-	-	-	-	-	yes				-	-	
1124cz	0.08	-	-	-	55	27	9	0	0	0	yes				-	-	
1124da	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	
1125db	-	-	-	-	-	-	-	-	-	-	yes				-	-	
1125dc	-	-	-	-	-	-	-	-	-	-	yes				-	-	
1125dd	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	
1125de	0.06	-	-	-	17	9	3	0	0	0	1	1	0	1	-	-	
1126df	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	
1126dg	-	-	-	-	-	-	-	-	-	-	yes				-	-	
1126dh	-	-	-	-	-	-	-	-	-	-	yes				-	-	
1126di	-	-	-	-	19	10	3	0	0	0	0	0	0	0	-	-	
1129dj	-	-	-	-	-	-	-	-	-	-	yes				-	-	
1129dk	-	-	-	-	-	-	-	-	-	-	yes				-	-	
1129dl	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	
1130dm	-	-	-	-	-	-	-	-	-	-	yes				-	-	
1130dn	-	-	-	-	-	-	-	-	-	-	yes				-	-	
1130do	-	-	-	-	-	-	-	-	-	-	6	6	1	8	-	-	
1201dp	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	
1201dq	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	
1201dr	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	
1202ds	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	
1202dt	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	
1202du	-	-	-	-	-	-	-	-	-	-	3	2	1	3	-	-	
1203dv	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	
1204dw	-	-	-	-	-	-	-	-	-	-	2	1	0	2	-	-	
1204dx	-	-	-	-	-	-	-	-	-	-	2	1	0	2	-	-	
1206dy	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	
1206dz	-	-	-	-	-	-	-	-	-	-	1	1	0	1	-	-	
1207ea	0.06	-	-	85	50	23	8	0	0	0	1	1	0	2	1.24	1.24	
1207eb	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	
1207ec	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	
1208ed	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	
1208ee	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	
1208ef	-	-	-	-	-	-	-	-	-	-	3	4	1	5	-	-	
1208eg	-	-	-	-	-	-	-	-	-	-	3	4	1	5	-	-	
1208eh	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	
1209ei	0.09	-	-	76	47	17	6	0	0	0	11	9	3	13	1.24	1.33	
1209ej	-	-	-	-	-	-	-	-	-	-	11	9	3	13	-	-	
1210ek	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	
1213el	-	-	-	-	-	-	-	-	-	-	1	1	0	1	-	-	
1214em	-	-	-	-	-	-	-	-	-	-	0	1	0	1	-	-	

-	-	-	-	1.83	1.75	1.62	-	-	-	-	3	86	0.024	77	11:04/15:10	04:00
-	-	-	-	2.14	2.15	1.81	1.76	-	-	-	3	89	0.018	84	11:08/16:10	04:20
-	-	-	-	2.39	2.41	2.30	2.15	-	-	-	3	89	0.016	86	11:09/13:05	03:20
-	-	-	-	-	-	-	-	-	-	-	3	-	0.017	-	11:09/15:30	02:25
-	-	-	-	2.39	2.32	2.24	-	-	-	-	3	89	0.019	84	11:10/12:30	03:10
-	-	-	-	-	-	-	-	-	-	-	11	-	0.020	-	11:10/15:50	03:20
-	-	-	-	1.39	1.47	1.60	-	-	-	-	7	73	0.022	80	11:11/12:30	02:55
-	-	-	-	-	-	-	-	-	-	-	4	-	0.021	-	11:11/15:20	02:50
-	-	-	-	2.07	2.08	2.05	1.59	-	-	5.1	12	61	0.043	64	11:12/14:00	03:30
-	-	-	-	2.02	1.99	1.87	-	-	-	-	4	86	0.017	87	11:15/13:20	03:30
-	-	-	-	-	-	-	-	-	-	-	3	-	0.023	-	11:15/15:35	02:15
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	11:16/16:00	03:25
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	11:17/11:05	01:25
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	11:17/13:05	01:35
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	11:17/14:15	01:00
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	11:17/15:30	01:05
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	11:17/16:20	00:45
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	11:18/10:35	01:10
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	11:18/12:05	01:20
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	11:18/13:30	01:15
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	11:18/14:50	01:10
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	11:19/12:00	02:00
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	11:23/13:30	04:25
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	11:24/10:35	01:20
yes				-	-	-	-	-	-	-	-	-	-	-	11:24/12:20	01:45
yes				-	-	-	-	-	-	-	4	-	0.006	-	11:24/13:45	01:25
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	11:24/14:55	01:05
yes				-	-	-	-	-	-	-	-	-	-	-	11:25/11:40	01:55
yes				-	-	-	-	-	-	-	-	-	-	-	11:25/13:20	01:40
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	11:25/14:45	01:25
1	1	0	1	-	-	-	-	-	-	-	3	-	0.006	-	11:26/09:55	18:30
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	11:26/12:10	02:00
yes				-	-	-	-	-	-	-	-	-	-	-	11:26/13:40	01:20
yes				-	-	-	-	-	-	-	-	-	-	-	11:26/15:30	01:45
0	0	0	0	-	-	-	-	-	-	-	5	-	0.003	-	11:27/13:00	21:20
yes				-	-	-	-	-	-	-	-	-	-	-	11:29/11:15	02:07
yes				-	-	-	-	-	-	-	-	-	-	-	11:29/13:45	02:30
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	11:29/15:45	02:00
yes				-	-	-	-	-	-	-	-	-	-	-	11:30/12:00	02:00
yes				-	-	-	-	-	-	-	-	-	-	-	11:30/14:20	02:15
6	6	1	8	-	-	-	-	-	-	-	-	-	-	-	12:01/09:45	19:15
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	12:01/12:30	02:25
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	12:01/13:40	01:05
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	12:02/09:45	20:00
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	12:02/11:45	01:45
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	12:02/14:00	02:10
3	2	1	3	-	-	-	-	-	-	-	-	-	-	-	12:02/16:00*	01:10
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-		-
2	1	0	2	-	-	-	-	-	-	-	-	-	-	-	12:04/14:00	03:30
2	1	0	2	-	-	-	-	-	-	-	-	-	-	-	12:04/15:10	01:10
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	12:06/13:55	03:45
1	1	0	1	-	-	-	-	-	-	-	-	-	-	-	12:06/16:00	02:00
1	1	0	2	1.24	1.24	1.12	1.00	-	-	-	8	70	0.006	93	12:07/13:10	02:25
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	12:07/15:00	01:45
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	12:07/16:25	01:25
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	12:08/10:45	01:25
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	12:08/13:00	02:10
3	4	1	5	-	-	-	-	-	-	-	-	-	-	-	12:08/14:25	01:25
3	4	1	5	-	-	-	-	-	-	-	-	-	-	-	12:08/15:45	01:15
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	12:09/09:35	17:45
11	9	3	13	1.24	1.33	1.27	0.95	-	-	-	-	-	0.007	90	12:09/13:00	03:00
11	9	3	13	-	-	-	-	-	-	-	-	-	-	-	12:10/10:05	21:05
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	12:10/13:00	02:35
1	1	0	1	-	-	-	-	-	-	-	-	-	-	-	12:14/10:50	25:02
0	1	0	1	-	-	-	-	-	-	-	-	-	-	-	12:15/11:00	24:00

Appendix D – Alum Analysis

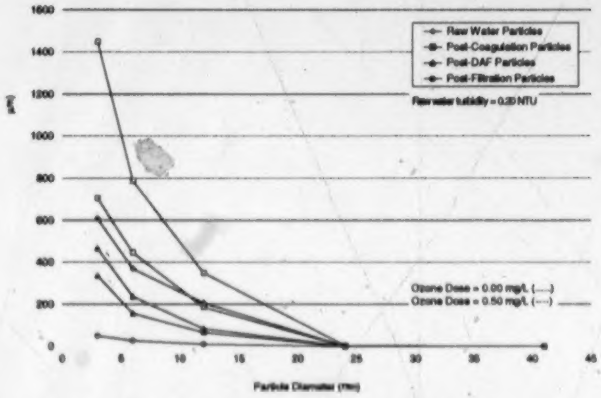


Figure D1. Effects of ozone on particle size distribution

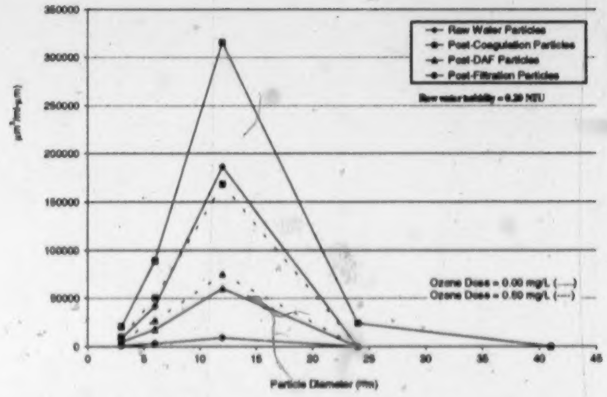


Figure D2. Effect of ozone on particle volume distribution

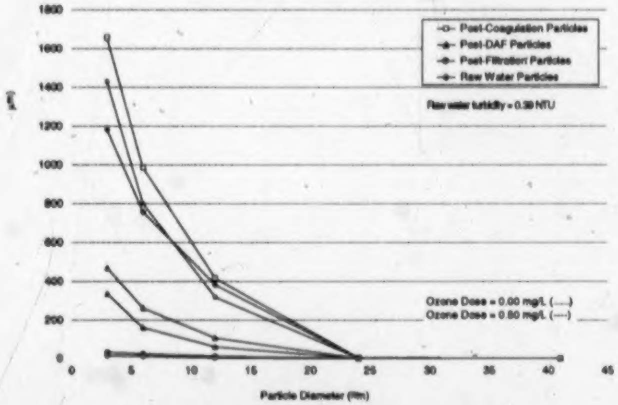


Figure D3. Effects of ozone on particle size distribution

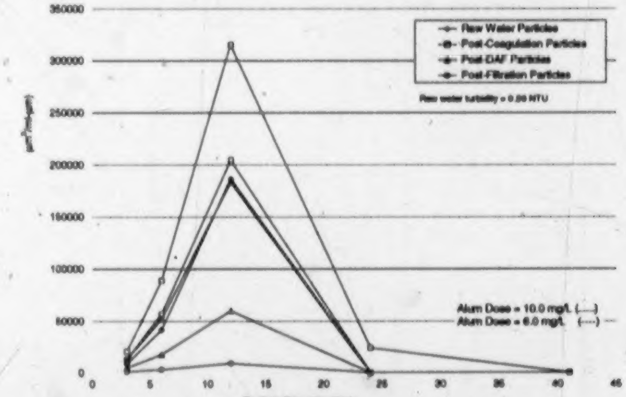


Figure D4. Effect of ozone on particle volume distribution

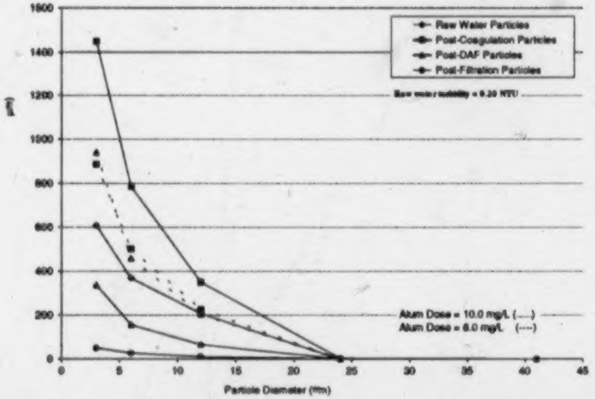


Figure D5. Effects of coagulant dose on particle size distribution

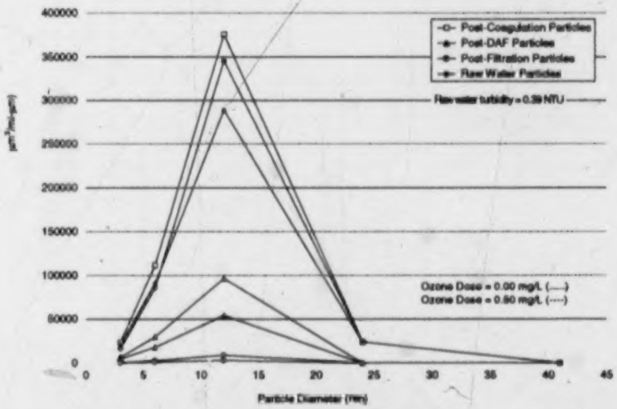


Figure D6. Effect of coagulant dose on particle volume distribution

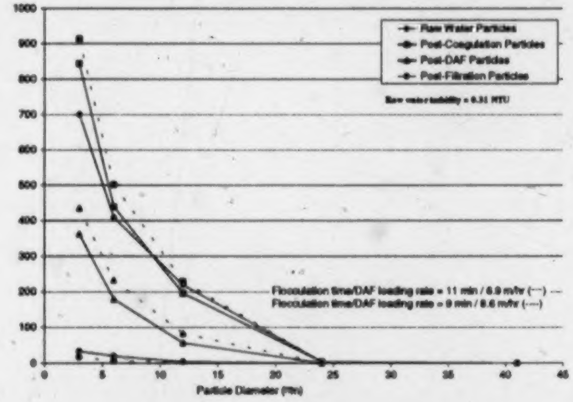


Figure D7. Effects of flow on particle size distribution

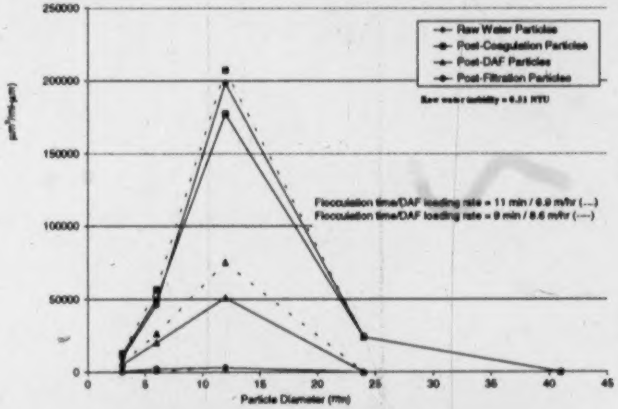


Figure D8. Effect of flow on particle volume distribution

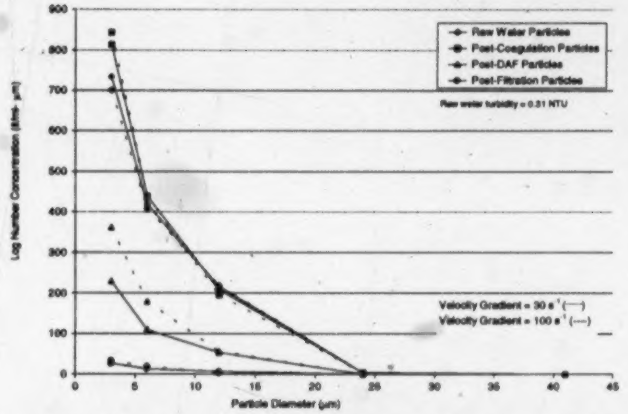


Figure D9. Effects of velocity gradient on particle size distribution

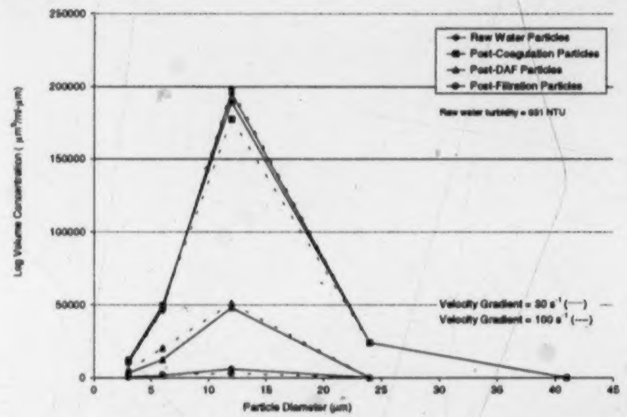


Figure D10. Effect of velocity gradient on particle volume distribution

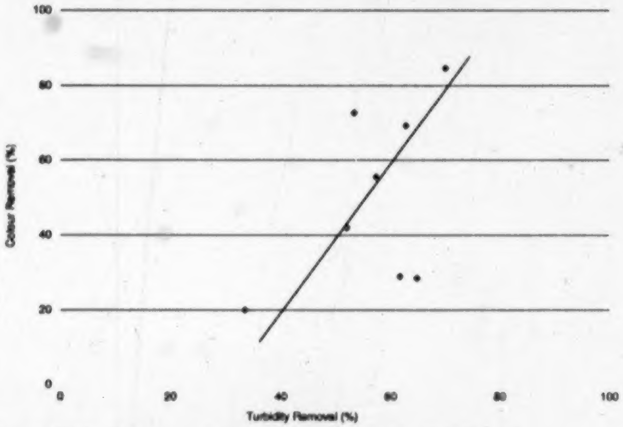


Figure D11. Colour and turbidity removal in DAF unit

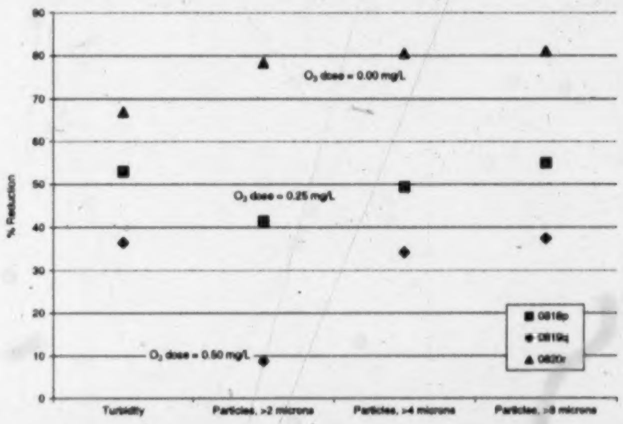


Figure D12. Effect of ozone on selected water quality parameters

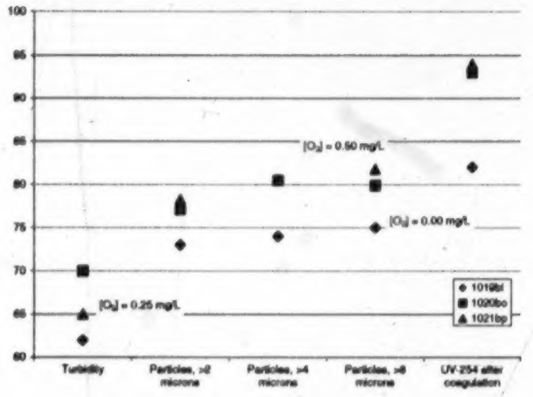


Figure D13. Effects of ozone on selected water quality parameters

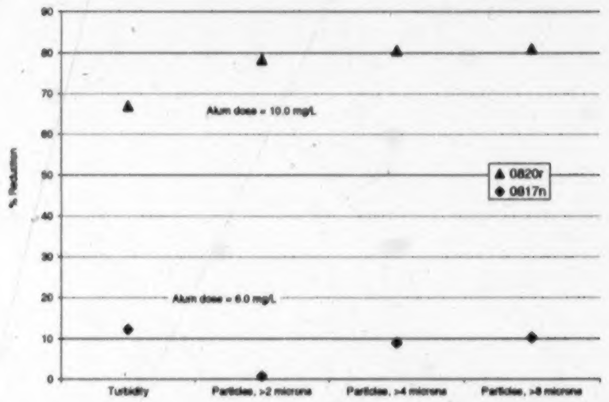


Figure D14. Effect of alum on selected water treatment parameters

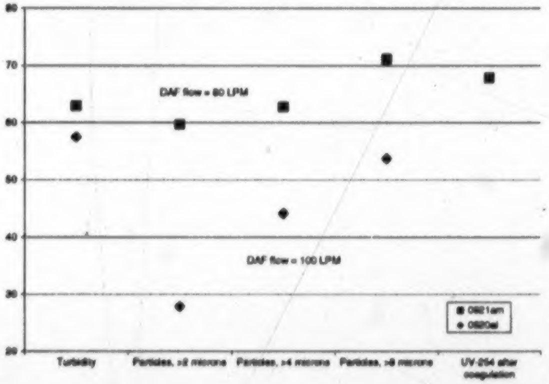


Figure D15. Effects of flow on selected water quality parameters

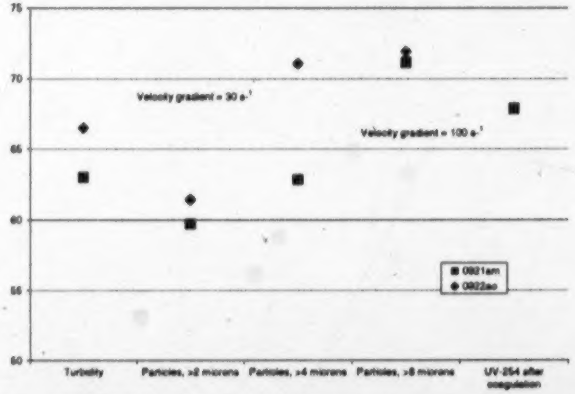


Figure D16. Effect of G on selected water treatment parameters

Appendix E – PACl Analysis

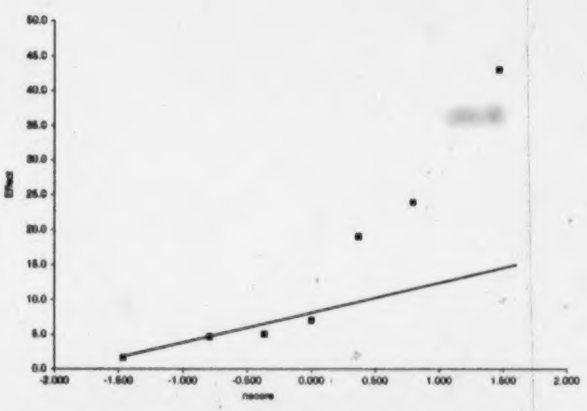


Figure E1. Normal Probability diagram for turbidity

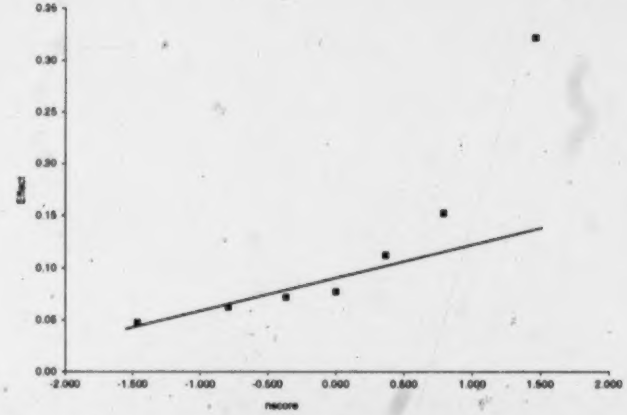


Figure E2. Normal Probability diagram for particles > 2 µm

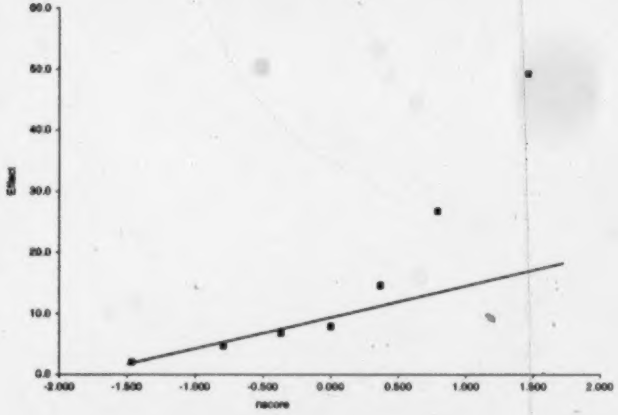
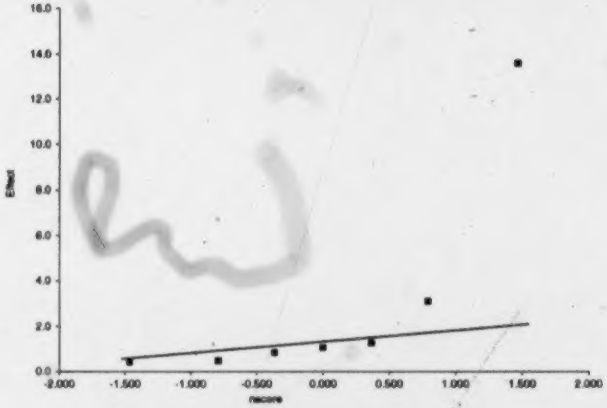


Figure E3. Normal Probability diagram for UV_{254}



3

Figure E4. Normal Probability diagram for turbidity

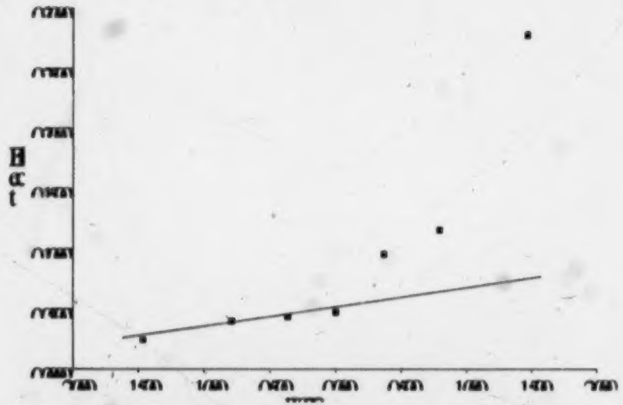


Figure E5. Normal Probability diagram for particles >2 µm

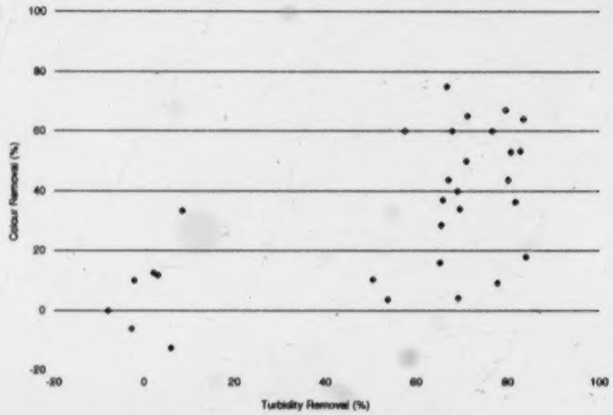


Figure E6. Colour and turbidity removal in DAF unit

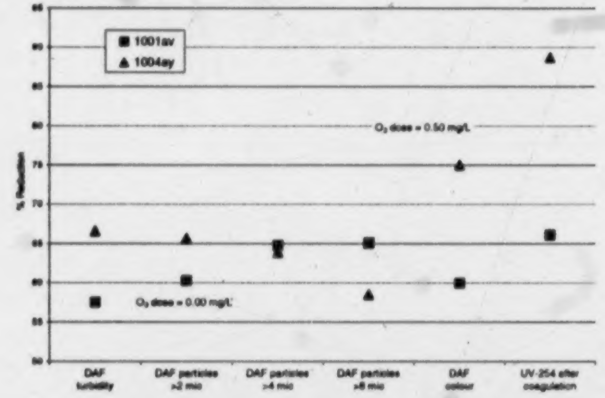


Figure E7. Effect of ozone on selected water quality parameters

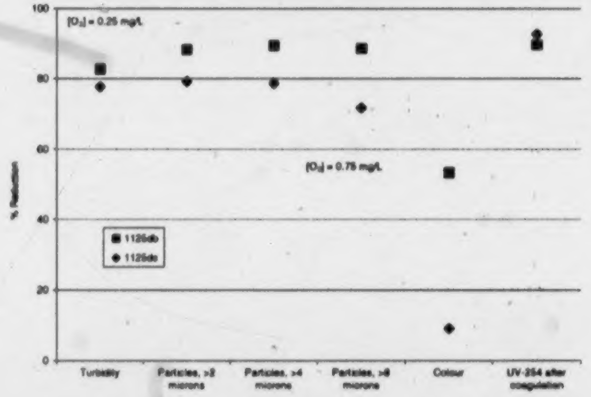


Figure E8. Effect of ozone on selected water treatment parameters

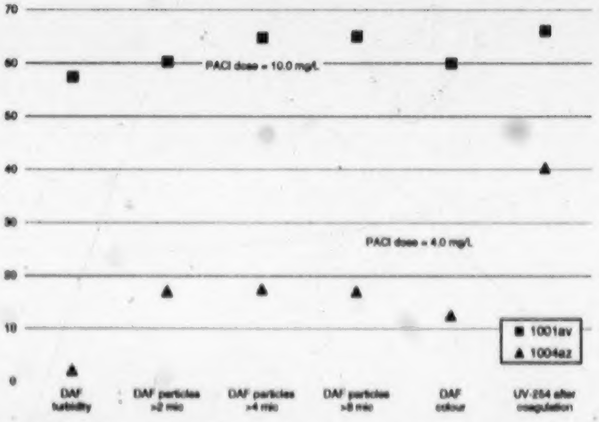


Figure E9. Effect of PACl on selected water quality parameters

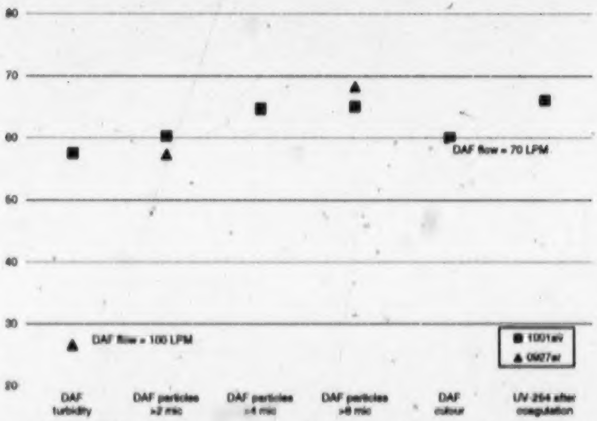


Figure E10. Effect of flow on selected water treatment parameters

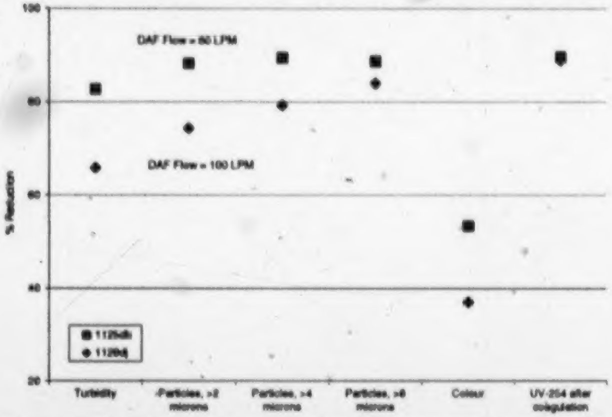


Figure E 11. Effect of flow on selected water quality parameters

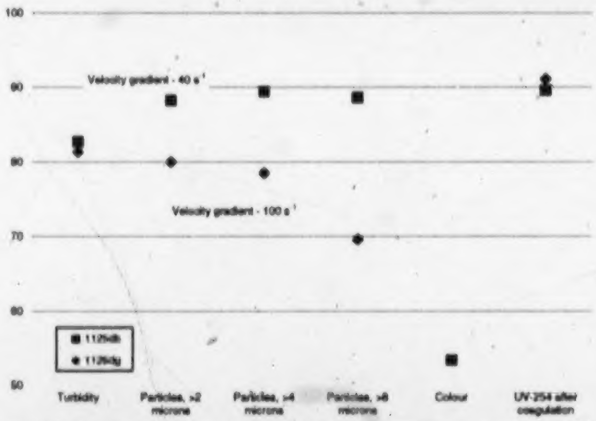


Figure E12. Effect of G on selected water treatment parameters

Appendix F – Ferric Chloride Testing

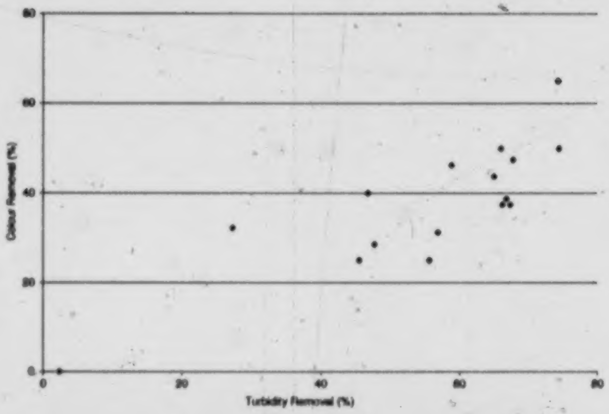


Figure F1. Colour and turbidity removal in DAF unit

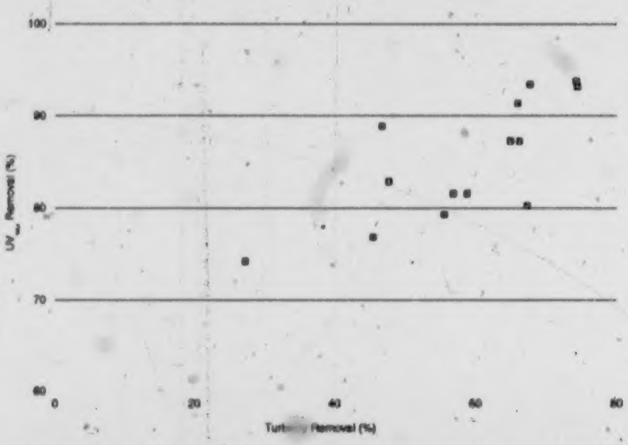


Figure F2. Relationship between turbidity and UV_{254} removal

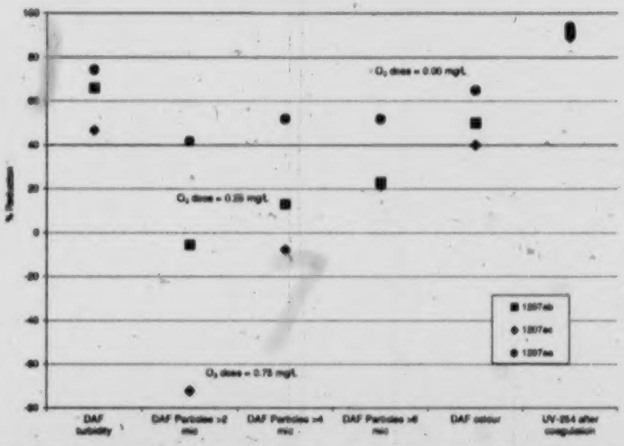


Figure F3. Effect of ozone on selected water quality parameters

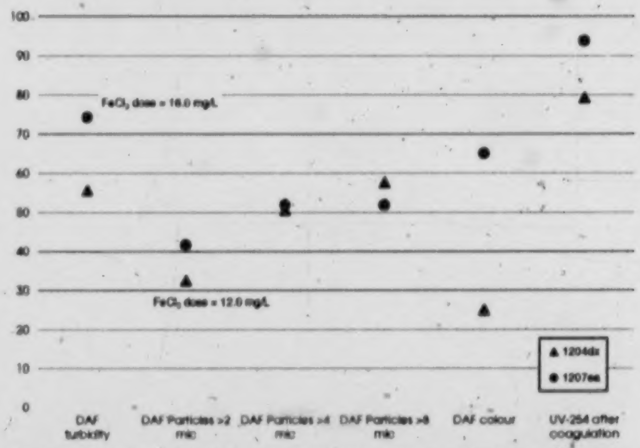


Figure F4. Effect of $FeCl_3$ on selected water quality parameters

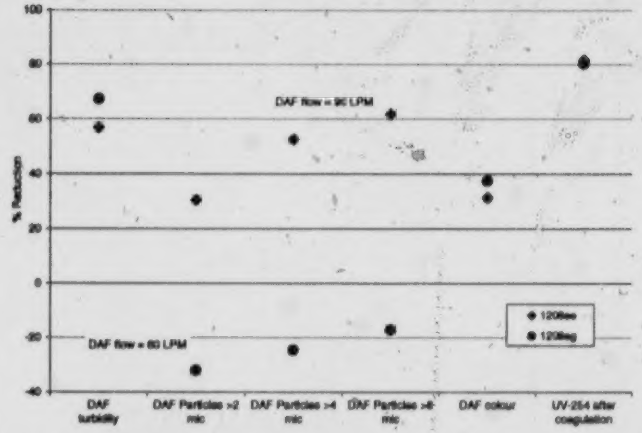


Figure F5. Effect of flow on selected water quality parameters

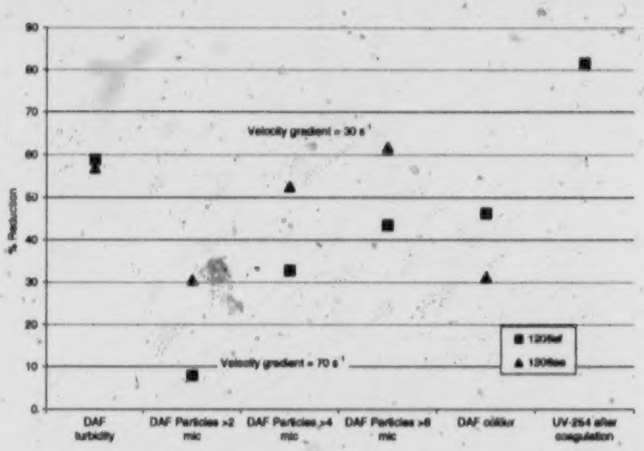


Figure F6. Effect of G on selected water quality parameters